First CO_2-neutral 145 kV Dead Tank Circuit Breaker and 145 kV / 50 kA GIS with Vacuum Switching and Clean Air Insulation Technology

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SUMMARY

Our power systems and grids are transforming rapidly, driven to realize a CO_2 neutral world and society. The reduction of CO_2 and equivalent greenhouse gases (GHG) is a key task to reduce global warming. For our power systems this means that the emission and use of SF_6, as strongest greenhouse gas, must be reduced and it's use eventually phased out. At the same time, performance and reliability must be kept or even increased.
California has taken regulatory action through the California Air Resource Board (CARB) to limit the leak-rate and phase out SF_6. An amended regulation for reducing sulfur hexafluoride emissions from gas-insulated equipment (GIE) and phase out of new SF_6 GIE has been approved for adoption [4]. SF_6 acquisition phase out dates for gas-insulated equipment are up to 145 kV in January 2025, up to 245 kV in 2027 and above in 2033. Californian utilities approach is to introduce equipment three or more years in advance to gather experience: for up to 145 kV this is 2022. Pacific Gas & Electric Co. acted and purchased the first 123 kV / 40 kA / 3000 A dead tank circuit breakers and first 123 kV / 50 kA / 3000 A GIS all with GHG-free clean air & vacuum technology in California.
This paper describes performance and test results of newest SF_6-free, F-gas free and GHG-free dead tank circuit breakers and GIS which use vacuum-switching technology up to 145 kV and complete CO_2-neutral insulation with clean dry compressed air. It shows the entire CO_2 neutral product portfolio: 72,5 kV Windtower GIS, up to 145 kV / 40 kA Live Tank and Dead Tank Circuit Breakers and 145 kV 50 kA gas-insulated switchgear (GIS) (in type testing) and free-standing gas-insulated Instrument Transformers and gas-insulated busbars up to 420 kV.
The vacuum switching technology has significant advantages compared to gas switching technology. The vacuum interrupter is the preferred solution for frequently operated switching and high short-circuit interruptions. The vacuum interrupter is a sealed for life component and thus completely maintenance free. For low temperature applications down to -60° C, the vacuum technology in combination with clean air insulation offers outstanding performance because no additional measures are necessary. With the new technologies – high-voltage vacuum switching and clean air insulation – upcoming switchgear are future proof with respect to health, safety, environment, and performance.
High-voltage vacuum interrupters up to 245 kV (single break) will be available in the next years commercially. The world's first vacuum interrupters for 170 kV / 50 kA and 245 kV / 63 kA were shown on CIGRE 2018. The latest operational experiences up to 145 kV and next developments on CO_2-neutral transmission equipment up to 550 kV were presented on CIGRE 2020 [5-7]. Based on recent developments on vacuum switching and clean air insulation technology new GHG-free products will replace common SF_6 switching equipment in the future. The latest product releases, deliveries and installations will be presented at Cigre Canada Exhibit 2021 on the booth and in a digital showroom.

KEYWORDS

Decarbonization, power grids, SF_6-free, Greenhouse gas free, CO_2 neutral, high voltage equipment, circuit breaker, gas-insulated switchgear, substation

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1 WHY

A sustainable world requires decarbonization of many parts of our society: energy, mobility, industry, and housing. The reduction of CO_2 and equivalent greenhouse gases (GHG) is a key task to reduce global warming. Electrification is the solution. Electricity generation and electrical grids must be decarbonized: generation using renewable energy and electrical grids by the application of greenhouse-gas free equipment. For our power systems this means that the emission and use of SF_6, the most potent greenhouse gas, and other GHG must be completely phased out and substituted by a healthy, safe, high-performing, and reliable technology. **Figure 1** shows the UN Sustainable Development Goals and the core goals for electrical grids.

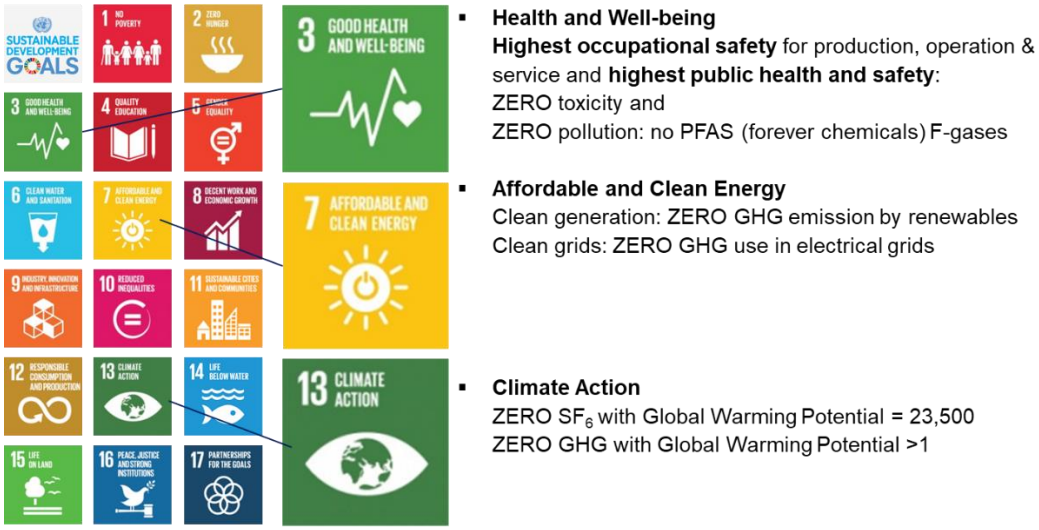

Figure 1: UN sustainable development goals and core goals for electrical grids

2 PG&E TAKES ACTION

PG&E provides safe, reliable, clean, and affordable natural gas and electricity to 16 million Californians. As part of PG&E broader commitment to address climate change, the company is working to realize 1MMT CO_2e emission reductions by 2022 and support Carbon Neutrality in California by 2045, **Fig. 2**.

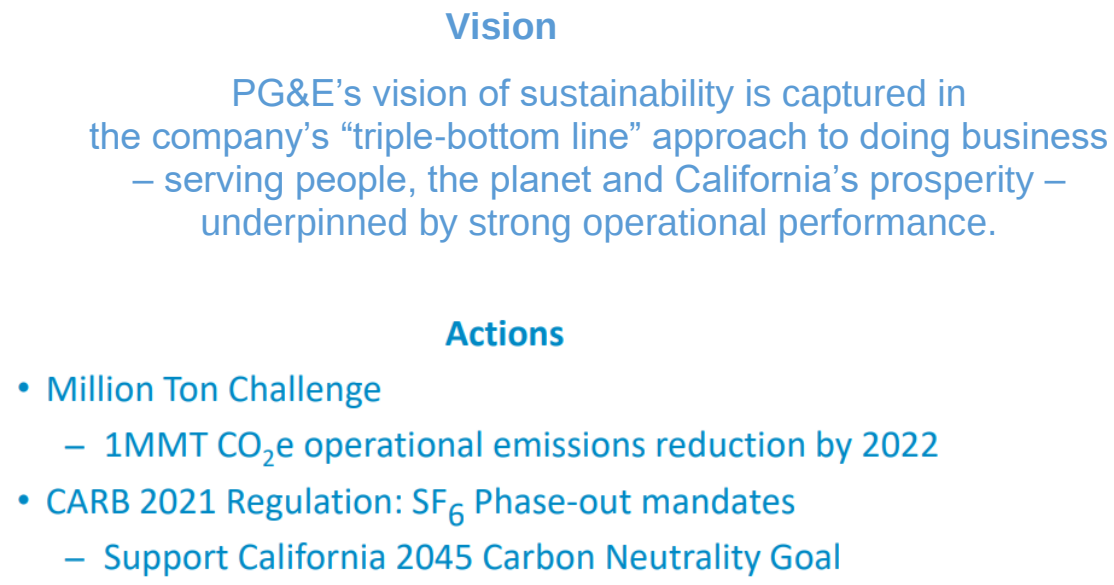

Figure 2: PG&E Vision and Actions

PG&E's Sustainability Leadership Council challenged its Transmission Substations department to come up with a plan to phase out the use of SF_6 in high-voltage gas-insulated equipment. The sourcing department completed a strategic supplier evaluation to identify SF_6 alternative suppliers for gas-insulated switchgear. The result: The Vacuum Switching – Air-Insulation technology is the preferred option based on technical, commercial, and quality evaluation criteria: technical performance, global warming potential, availability of suppliers, and no F-gas-reporting requirements [1].

Table1: Technical Requirements Evaluated

Specifications	Dry Air/Vacuum	Novec 4710	Novec 5110
Installed Base GIS DTCB LTCB	>100 wind-tower GIS at 72 kV, 40kA >10 multi-bay GIS at 145 kV, 40 kA >1000 DTCB at 72.5 kV, 40 kA Yes LTCB	<10 multi-bay GIS at 115 kV, 40 kA 1 multi-bay GIS at 230 kV, 63 kA 1 multi-bay GIS at 72 kV, 32.5 kV No DTCB Yes LTCB	One multi bay GIS at 115kV 40kA. No DTCB Yes LTCB
Boiling Point, °F (°C)	-317 (-194)	-30 (-34)	41F (5)
Dielectric Strength with SF6 being 1	0.43	0.92	0.7
Decomposition Products	None	Equal to SF_6	Equal to SF_6
Installed Base in California	Yes, 72 DTCBs installed	No	No
Installed at PG&E	Yes, since 2010	No	No
Maintenance Cost	Lower than SF_6	Same as SF6	Same as SF_6
If Rating	63 kA	40 kA DTCB	40 kA
V Rating maximum, kV	550kV	145 kV	145 kV
Size (GIS)	Larger than SF_6	Same as SF_6	Larger than SF_6
Size (DTCB)	Same as SF_6	Same as SF_6	Larger than SF_6
Type Tested for U.S.	DTCB 72 kV, 40 kA, 3000 A LTCB 145 kV, 40 kA GIS 145 kV, 40 kA	No No No	No No No
X/R Rating at 60 Hz	17 (tested)	Unknown	Unknown

Notes:
1. **Yellow highlights denote preferred property.**
2. Data taken from information supplied by multiple suppliers in response to PG&E's request for information in 2016.

Table 1: Technical requirements and evaluation from PG&E supplier evaluation [1]

California is the first state which has taken regulatory action through the California Air Resource Board (CARB) to limit SF_6 emissions and phase out SF_6. Beginning with reporting year 2025, the requirement changes to an emissions limit, rather than a rate. The revised regulation order of reducing greenhouse gas emissions for all gas-insulated equipment and phase out of SF_6 has been approved for adoption [4]. SF_6 phase out dates for gas-insulated equipment are shown in **Table 2**.

Voltage Capacity (kV)	Short-Circuit Current Rating (kA)	Phase-Out Date
38 < kV ≤ 145	< 63	January 1, 2025
	≥ 63	January 1, 2028
145 < kV ≤ 245	< 63	January 1, 2027
	≥ 63	January 1, 2031
> 245	All	January 1, 2033

Table 2: Phase-out dates for acquisition of SF_6 GIE (gas-insulated equipment) in CARB proposed regulation [4]

Californian utilities approach is to introduce equipment three or more years in advance to gather experience: for up to 145 kV this is 2022. Pacific Gas & Electric Co. acted and purchased the first 123 kV / 40 kA / 3000 A dead tank circuit breakers and first 123 kV / 50 kA / 3000 A GIS all with clean air and vacuum switching technology in California. The PG&E way and learnings on how to drive the change are listed in **Figure 2**.

- **Recognize the Risks & Opportunity**
  - SF6: Highest known global warming potential (23,500)
  - SF6: Environmental persistence (3,200 years)
  - SF6: No available commercial waste gas management
  - **Dry-Air/Vacuum**: Safe and reliable alternative
- **Communicate the Value**
  - Initiate pilot projects and share findings with peer utilities
  - Encourage other utilities & stakeholders to pursue alternatives, create market need
  - Support Supplier communication with Regulators
- **Drive the Change**
  - Phase-out Charter and Roadmap
  - Collaborate with GIE Suppliers
  - Educate stakeholders: Leaders, Engineers, Project Managers
  - Support CARB Regulation
  - Support incentives: Fund pilot projects, Early Action Credit

Figure 2: PG&E way and learnings on how to drive the change to sustainable grids [3]

3 GHG-free HV-products for decarbonized power grids

How to eliminate SF_6 and introduce a technology which has a comparable high reliability, even increased performance and is at the same time the most sustainable solution for Health, Safety, and environment? To solve that task Siemens Energy did intensive research on over 200 gases regarding insulating and switching performance. The most promising gases are compared to SF_6 in **Table 3**. Conclusion: There is no alternative gas combining all the benefits. Clean Air is the most sustainable solution with the highest number of preferred properties and with no compromises regarding Health, Safety and Environment.

	SF_6	Clean Air	F-Gas-mix based on Fluoronitrile
Chemical formular	SF_6 	$N_2 + O_2$ (79,5%/20,5%) 	C4F7N 
CO_2-equivalent / GWP_{100} (100 years horizon)	22.800 (IPCC AR4) 23.500 (IPCC AR5) 25.200 (IPCC AR6 2022)	0	2.100 (Manufacturer data) 2.750 (New in IPCC AR6 2022)
Boiling point (°Celsius)	-64°	< -183°	-4,7°
Life time (years)	3.200	-	30
Carrier gas	Pur or mixed with N_2, CF_4	-	CO2 + C4F7N and in some cases + O2
CO_2-equivalent / GWP_{100}	25.200	0	> 500 based on applications
Boiling point (°Celsius)	<- 64° (variable)	< -183°	-30°...-25°C dependant on C4F7N amount
Dielectric strength	1 (normalized)	~ 0,4	~ 0,7
Arcing impact			
Dissociation/decomposition	~ 2000 K (reversib.)	~ 7000 K (N2 reversib.)	> 920 K (irreversib.)
Decomposition products	HF, SO_2, sulphur compounds	None under normal operating conditions (VIU) If failure: Ozone, NOx	F-Nitrile [4]: HF, CO, COF_2, CF_3CN, C_2F_5CN, C_2F_6 C5-K. [6]: HF, CF_4, C_2F_6, $C_5F_{10}O$, C_3F_8, C_4F_{10},C_3HF_7 C_4F_8, C_4F_6, C_3F_6, C_2F_3N, C_2N_2 in MV GIS with air

Preferred property Compromised property

Table 3: Properties of SF_6 and alternatives

Next step was to evaluate the insulating and switching performance of the gases. To achieve the goal of performance increase, the well-known and highly reliable vacuum-switching technology was further developed to the next voltage levels. The results of the performance evaluation are shown in **Figure 3**.

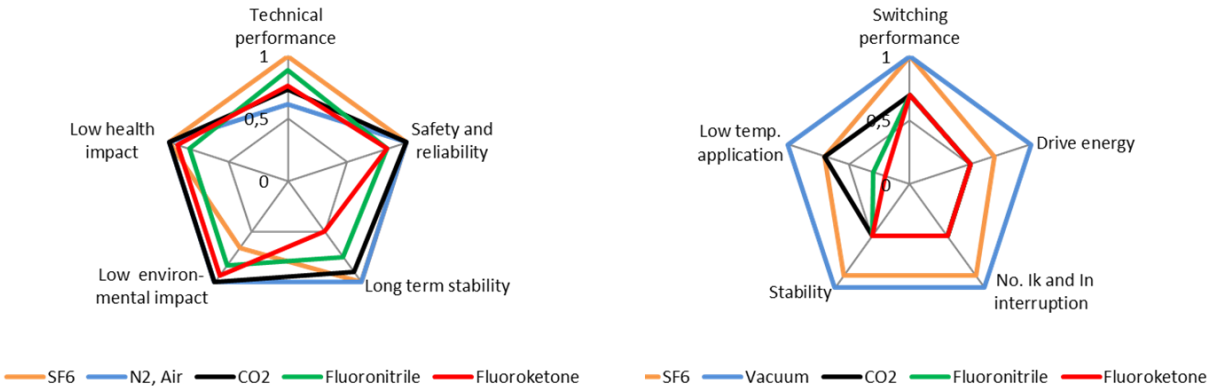

Figure 3: Evaluation of SF_6 and alternatives regarding insulating and switching performance [5]

Clean Air insulation technology (left figure in blue) has the highest values for Health, Safety, Environment, and long-term stability. The lower dielectric strength must be considered in the product design. The vacuum switching technology (right figure in blue) has significant advantages compared to gas switching technology applications. The vacuum interrupter has a strong switching performance, with a higher number of short circuit and rated current interruptions. With less energy generated during switching it is having lower contact erosion and requires less drive energy. Is perfect for low temperatures down to –60°C, sealed for life with no interrupter maintenance.

Next step was the evaluation of operational performance, which is summarized in **Figure 4**.

		Vacuum + Clean-Air	SF_6	F-Gas-Mix
Health, Safety & Environment	Gas handling	✚	○	▬
	Decomposition products	✚	▬	▬
	Toxicity	✚✚	○	▬
	GWP	✚✚	▬	○
Operational performance	Switching rated current	✚✚	✚	○
	Degradation of switching media	✚✚	○	▬
	Long term stability	✚✚	✚✚	uncertain
	Gas tightness	✚	✚	▬
Maintenance	Maintenance of interrupter unit	✚✚	○	▬
Reporting / Regulation	Current and future proof	✚✚	▬	▬

✚✚ Outstanding performance ✚ Good performance ○ Average performance ▬ Performance below average

Figure 4: Operational Evaluation SF_6 and alternatives

Based on the requirement and feedback of the grid owners and operators, it was clear to substitute SF_6 technology with the most sustainable alternative: Vacuum-switching and Clean Air insulation technology, **Figure 5**.
First vacuum circuit breakers were installed 2010. Meanwhile a whole portfolio of circuit breakers, instrument transformers and gas-insulated switchgear has been developed and is in reliable and successful operation, **Figure 6.**

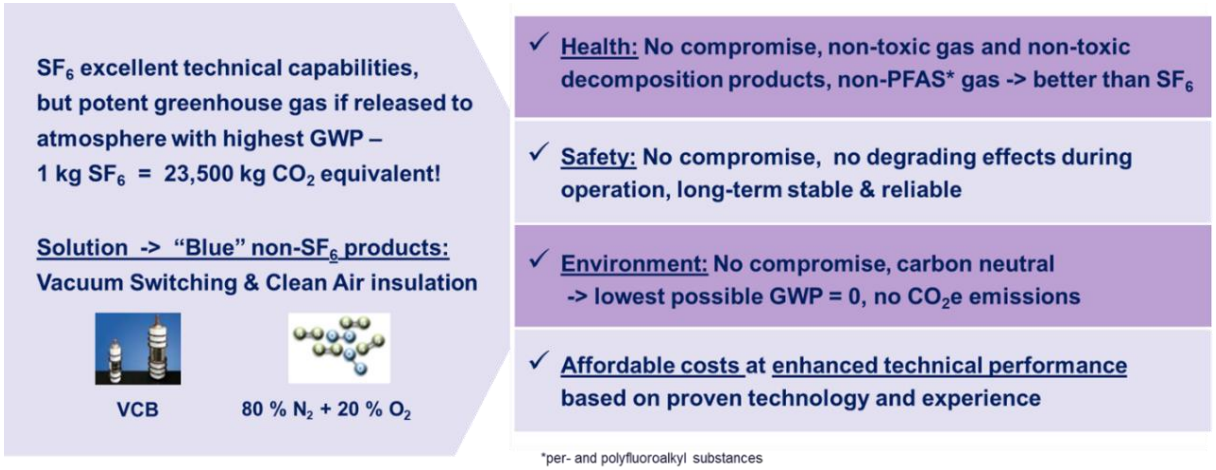

Figure 5: Values of vacuum switching and clean air insulation technology

Figure 6: Current portfolio of GHG-free HV-equipment: >1500 units contracted; >400 units in operation

4 GHG-free Dead Tank Circuit Breakers up to 145 kV

In 2016, PG&E initiated a request for information on SF_6 free HV-products. In 2017, CARB invited for a public workshop on amendments on the SF_6 regulation and Siemens Energy presented their HV-products and roadmap with no SF_6, nor any other F-gas and completely free of any GHG. It became soon very clear that PG&E, CARB and Siemens Energy share the same vision and mission on a sustainable electrical transmission & distribution, completely SF_6-free and with no GHG. In 2018, PG&E purchased the first 123 kV / 40 kA / 3000 A dead tank circuit breakers (**figure 7**) and first 123 kV / 50 kA / 3000 A GIS with clean air and vacuum switching technology globally for the installation in California.

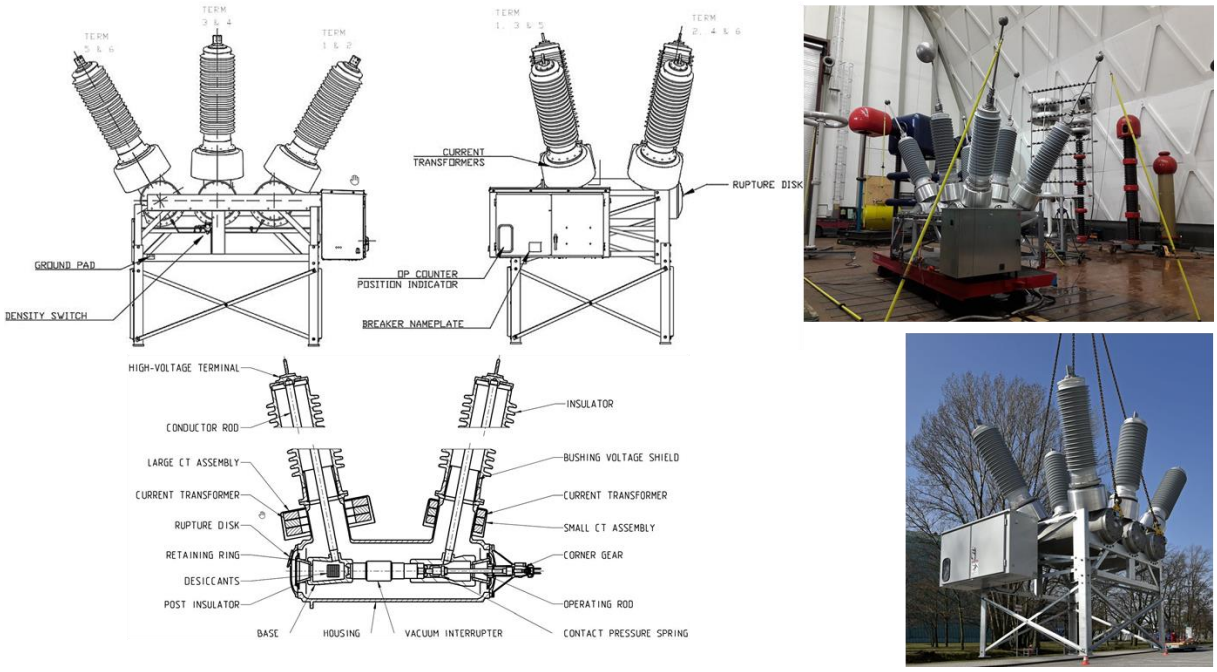

Figure 7: First order outline, 123 kV, 40 kA Dead Tank Circuit Breaker with Vacuum Interrupting and Clean Air insulation technology, HV-type testing, and type-tested product

An intensive dialogue with factory visits in Jackson and Berlin started. Joint design reviews were conducted, and main tests were eye-witnessed. This successful partnership work passed an important milestone in the first half of 2021 with the completed type test according to IEEE/ANSI standards (**figure 8**) for the 123 kV / 40 kA / 3000 A dead tank design. The delivery of the first dead tank circuit breakers is planned for the second half of 2021. Next steps are the type tests for 145 kV / 40 kA with the first deliveries planned for 2022 and in a third step the type test and first deliveries for 145 kV / 63 kA in 2023.

Power Tests		Dielectric Tests	Mechanical Tests	Confirmations
✓ T10	✓ STC / PWC	✓ Power freq. voltage withstand	✓ Mechanical endu-rance incl. CC & IC	✓ Dielectric test of auxiliary and control circuits
✓ T30	✓ Verification test	✓ Lightning impulse voltage	✓ Temperature rise	✓ EMC
✓ T60	✓ Line and Cable Charging (LC/CC)	✓ Chopped wave (Tc ≥ 2 µs)	✓ Seismic calculation for IEEE high (1g)	
✓ T100s (a+b)	✓ TLF 1	✓ Visible corona and RIV	✓ Static terminal load	
✓ T100a	✓ TLF 2	✓ X-ray test	✓ Low and high temperature test in acc. to IEEE C37.04 + C37.06 + C37.09 DT -60°C GIS -50°C	
✓ OP2		✓ Partial discharge	✓ Sound pressure level	
✓ L75				
✓ L90				

Figure 8: 123 kV / 40 kA / 3000 A Dead Tank Circuit Breaker with Vacuum Interrupting and Clean Air insulation technology, **completely type tested down to -60°C**

5 GHG-free Gas-insulated switchgear up to 145 kV

The 145 kV / 40 kA / 3150 A GIS is completely type tested according to IEC and IEEE (**figure 9 and 10**). More than 150 bays are contracted and more than 20 in operation. Next important milestone is the completion of the type test for the 123 kV GIS for 50 kA in 2021 and the first delivery to PG&E substation Hunters Point in San Francisco, California in 2022.

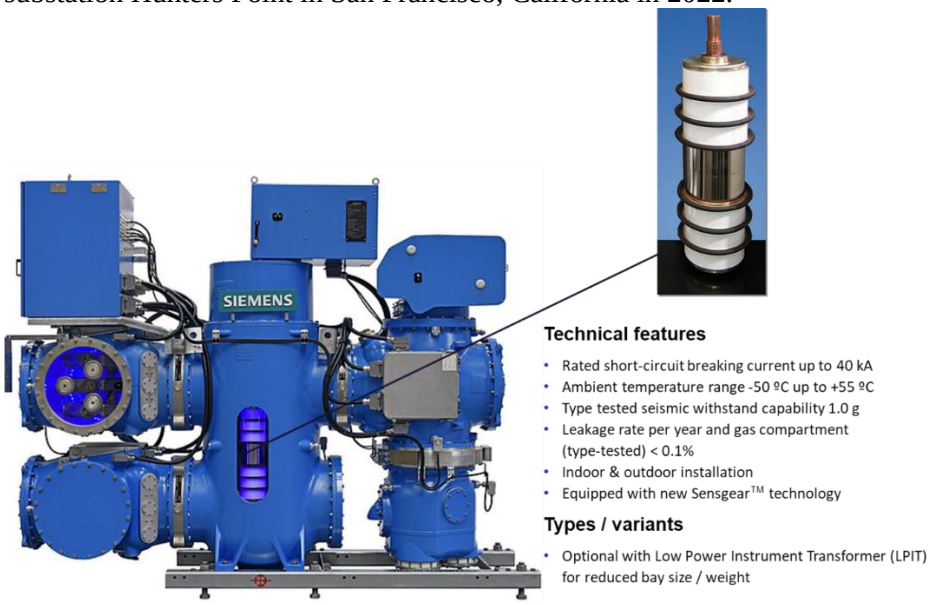

Figure 9: Clean Air Vacuum Blue GIS 145 kV / 40 kA / 3150 A / -50°C / 1g – Technical features

✓ **Type tests according IEC / IEEE passed**

Voltage: U_r, U_p, U_d	145 kV / 275 kV / 650 kV
Current I_r, I_{sc}	up to 3150 A / 40 kA (3s)
Rated frequency f_r	50 / 60 Hz
Temperature range	-50 °C...+40 °C w/o liquefication & rating reduction
Class classification	C2, E2, M2
Capacitive performance	LC/CC/BC
Min. nom. current switching operations Ir	10.000 versus SF_6-CB typically 6.000
Min. short-circuit current operations Isc	30 versus SF_6-CB typically 6
Interrupter- / Insulation Technology	Vacuum / Clean Air (synthetic air with 80 % N2 + 20 % O2) w/o any other chemical substances
First major inspection / Expected lifetime	> 25 years / > 50 years
Standards	IEC / IEEE

Main technical benefits in comparison to SF_6 GIS beside GWP = 0

Figure 10: Clean Air Vacuum Blue GIS 145 kV / 40 kA type tests completed
50 kA type tests in 2021, first 50 kA delivery to PG&E in 2022

6 Summary and Outlook

F-gas-free, clean air & vacuum switching technology sets the new sustainability standard for GHG-free global power grids of the future. Main values for society, grid owners and operators are:

1. Zero emission: No GHG, GWP = 0
2. Zero pollution: non-toxic, non-hazardous, F-gas and PFAS-gas (forever chemicals)-free. No special health and safety requirements
3. Out of any F-gas & chemical regulations now & in future
4. No degrading effects during operation. Long-term stable and reliable with improved technical performance
5. Multiple gas suppliers, simple gas handling, no unknown end-of-life risks and costs due to not available commercial waste F-gas destruction or disposal

The latest operational experiences up to 145 kV and next developments on CO_2-neutral transmission equipment up to 550 kV were presented on CIGRE 2020 [5-7], **figure 11**. Development and testing of vacuum interrupters for 145kV / 40kA and 63kA dead tank breakers is underway. Vacuum interrupters up to 245 kV (single break) will be available in the next years commercially. Based on recent developments on vacuum switching and clean air insulation technology new CO_2-neutral products will replace common SF_6 switching equipment in the future. All new GHG-free products can be additionally equipped with IoT connectivity and intelligence to support operation, asset management and service to support the new requirements of fluctuating renewable generation, possible grid congestions, asset optimization and predictive maintenance [8].

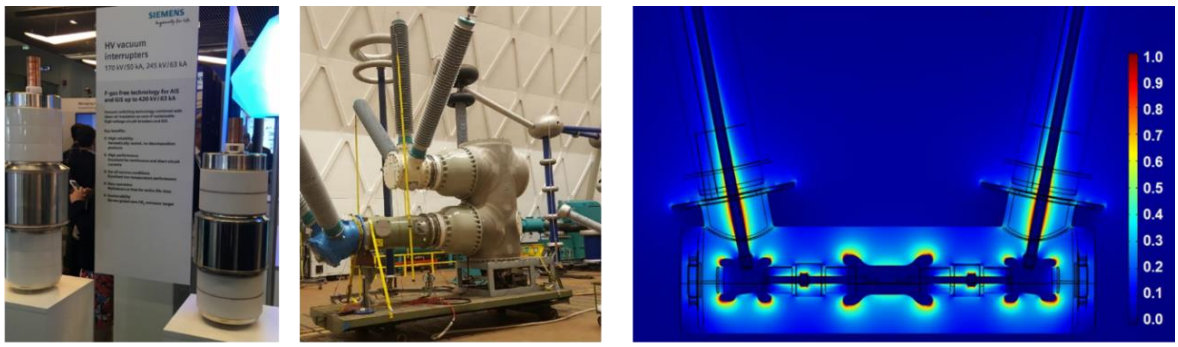

Figure 11: Single-break vacuum interrupter up to 245 kV are in development and double-break vacuum interrupter Dead Tank Breaker technology up to 550 kV feasibility studies successful

The latest product releases, deliveries and installations will be presented at Cigre Canada Exhibit 2021 on the booth and in a digital showroom.

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