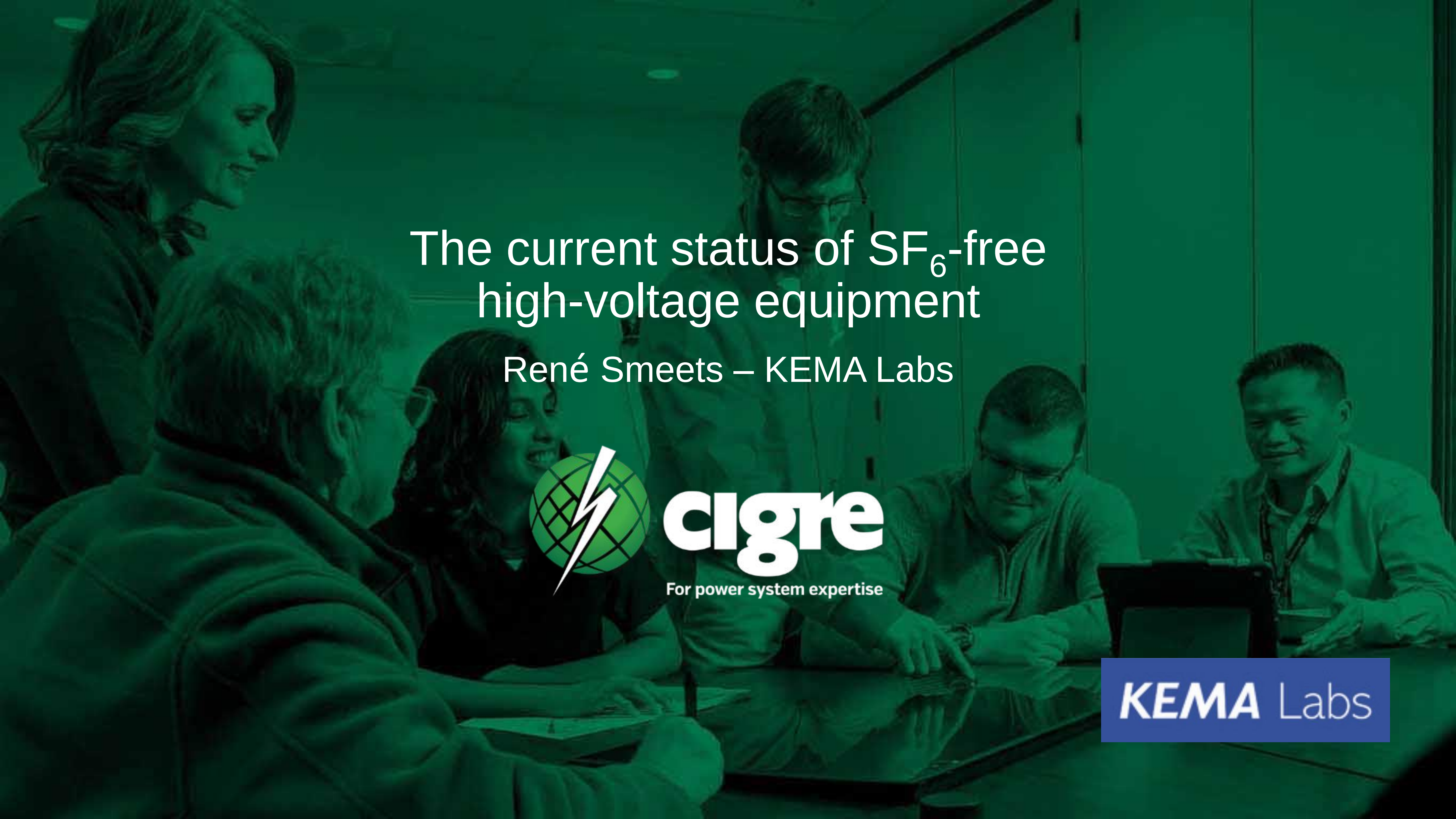
1 February 2024

Towards net-zero emission of T&D grids



The current status of SF_6-free high-voltage equipment

René Smeets – KEMA Labs

cigre

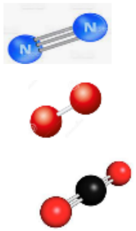
For power system expertise

KEMA Labs

SF_6 gas alternatives

- Insulation: GIS, GIL, GIB, instrument transformers
- Switching (current interruption): Circuit breakers, switches, disconnectors

natural-origin gases

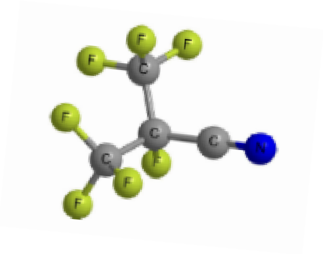


N_2
O_2
CO_2
} air

various mixtures

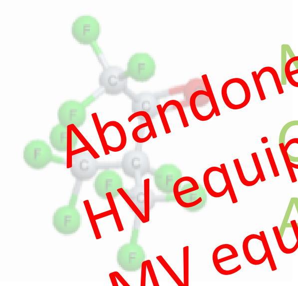
- GWP < 1
- Insulation only (switching in vacuum)

fluoronitriles



Novec™ 4710
C4-FN
g^3

fluoroketones



Novec™ 5110
C5-FK
AirPlus

Abandoned by industry:
HV equipment 2021
MV equipment 2023

5 % in a mixture with CO_2 (and mostly O_2)

- GWP 2750
- In mixture GWP < 1000
- F-gas, PFAS substance
- Insulation and switching

- GWP < 1
- In mixture GWP < 1
- PFAS substance
- Insulation and switching

Abandoned by industry:
HV equipment 2021
MV equipment 2023

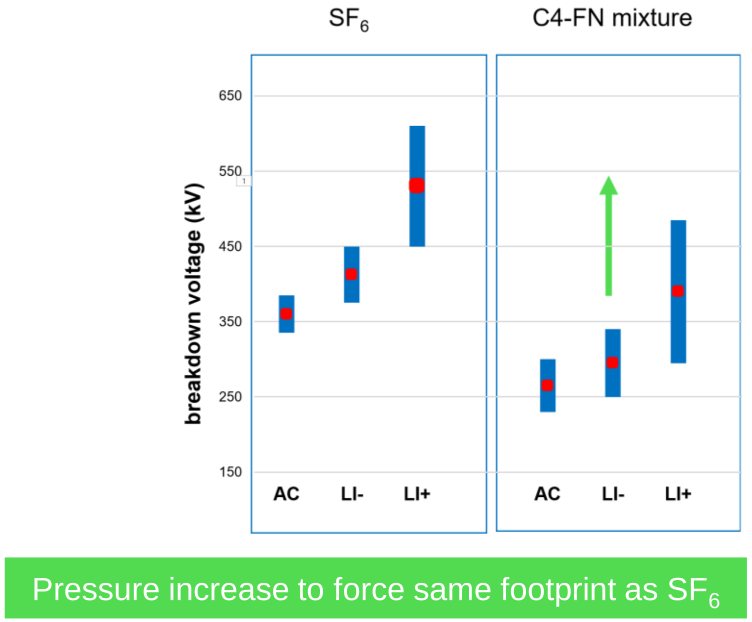
Different performance of C4-FN based mixtures vs. SF_6

- Lower critical electrical field
  - Lower breakdown voltage
    -> higher pressure and/or larger size required
    “new” size close to 1990-2000 size

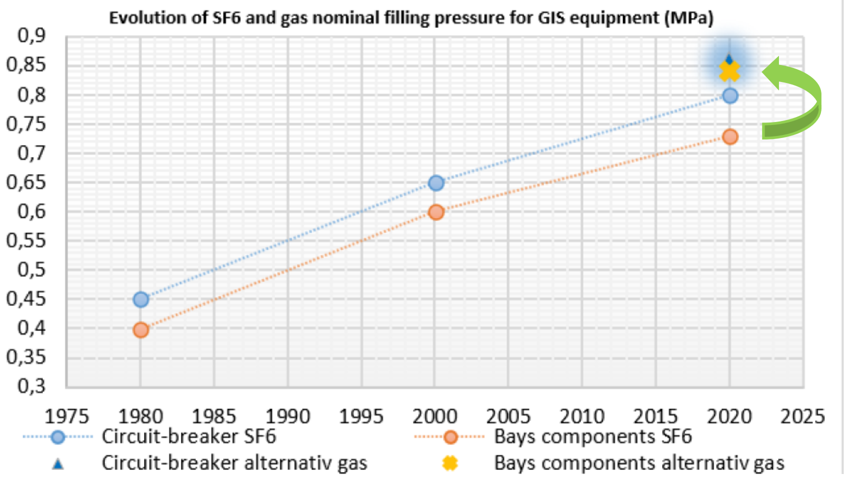
- CO_2 smaller molecule compared to SF_6
  - EPDM (Ethylene Propylene Diene Monomer) has high leakage
    -> butyl rubber

- Different thermal effusivity
  - Lower convective heat transfer (GIS)
    -> higher temperature rise

- High boiling point of fluorinated compounds
  - Limits ‘’very cold” applications
    -> reduce the fraction of F-gas or leave out

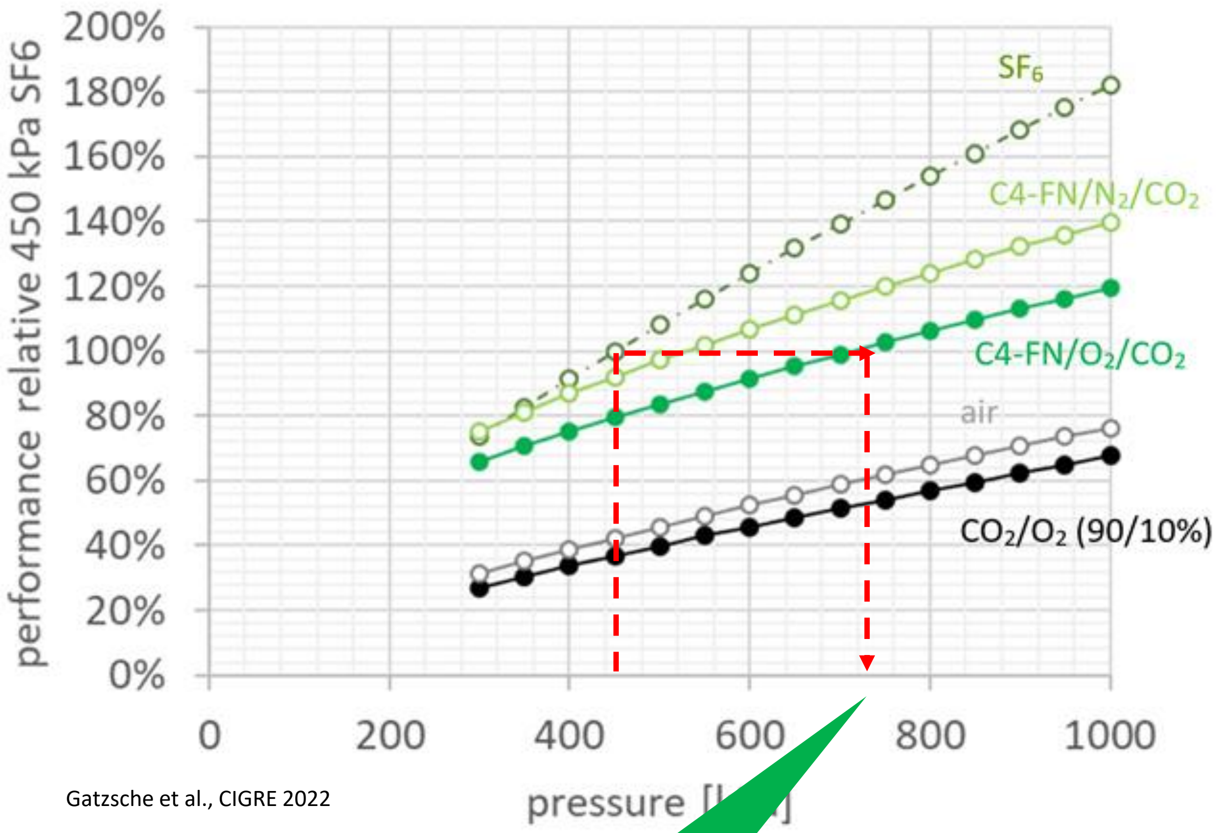


CIGRE TB 849, 2021



Blanchet, CIGRE Cairns 2023

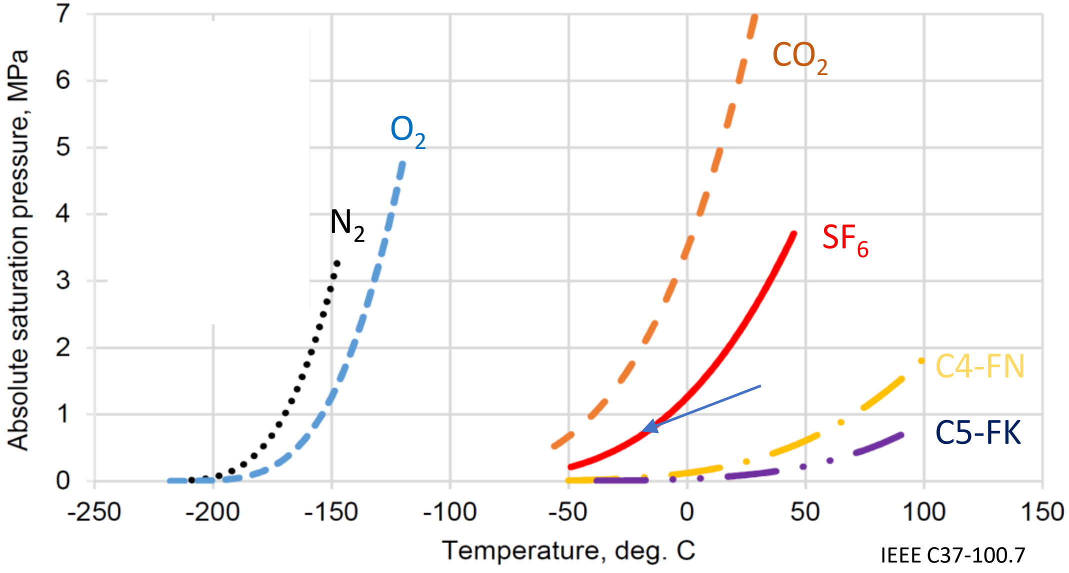
Challenge: low minimum operation temperature



Gatzsche et al., CIGRE 2022

Pressure increase 4.5 -> 7.5 b

phase diagram
liquid <-> gas



IEEE C37-100.7

- Higher gas pressure:
  - condensation at higher temperature
  - minimize the partial pressure of effective gas
- Not an issue with natural origin gases

Fault current interruption function: circuit breakers


live tank circuit breaker (LT)

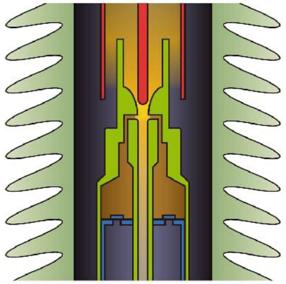

dead tank circuit breaker (DT)

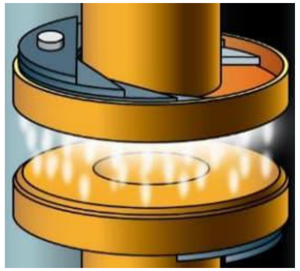

GIS circuit breaker

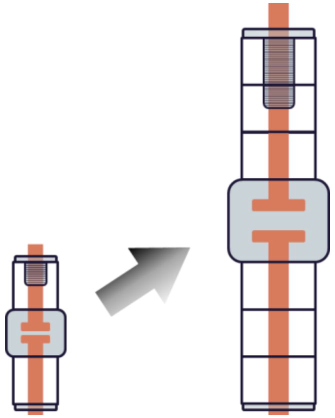
Two technologies:

- Gas (SF_6) circuit breakers
  - All voltage levels 10 – 1200 kV
  - outside insulation open air or SF_6
  - now available with SF_6-free synthetic gases

- Vacuum circuit breakers
  - main workhorse in distribution
  - introduced in transmission (Japan > 2005)
  - originally with SF_6 outside insulation
  - now available with SF_6-free insulation







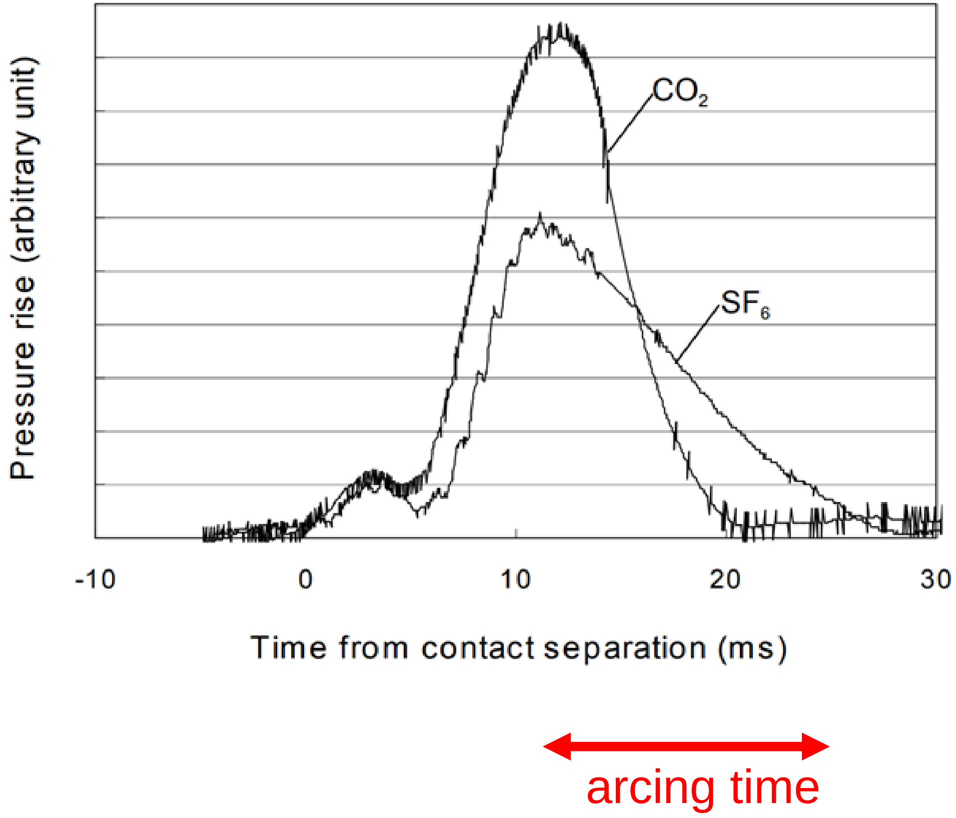
Different performance of C4-FN mixture vs. SF_6 in interruption

- CO_2 has higher speed of sound
  - Faster flushing of the arcing zone
    -> Larger compression volume, valves re-design

- CO_2 has lower adiabatic index
  - High transient pressure during interruption
    -> re-enforce arcing chamber

- Lower critical electrical field
  Affects recovery after interruption
    -> may require higher opening velocity

- Decomposition of fluorinated compounds under arcing
  - May impact electrical life
    -> have enough gas on board

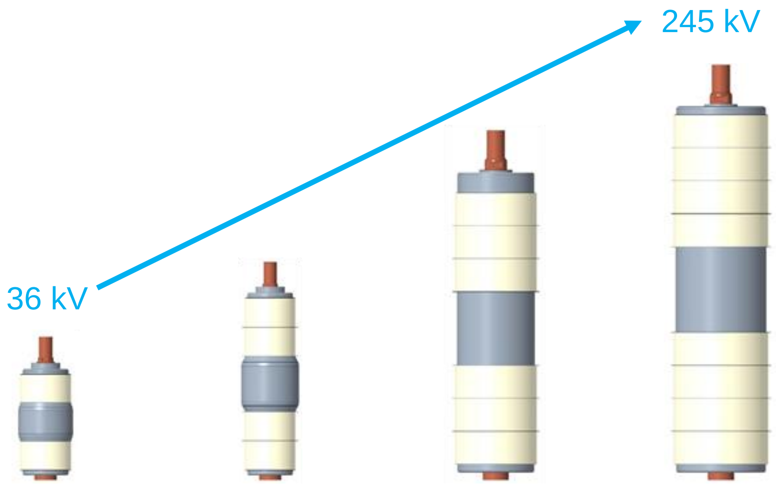


Uchii, T., et al. 'Fundamental research on SF6-free gas insulated switchgear adopting CO2 gas and its mixtures', In: Proceedings of the International Symposium on Eco Topia Science (2007).

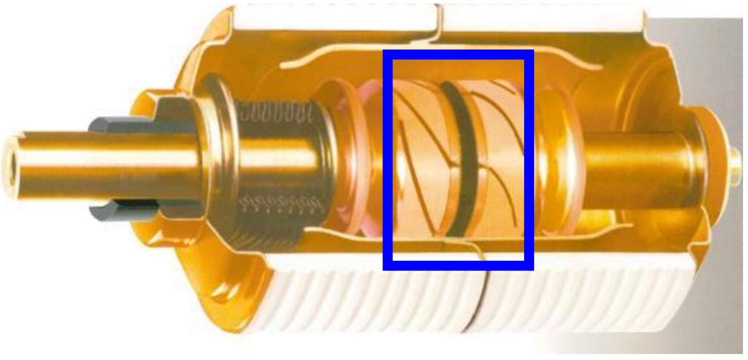
Vacuum + compressed air for outside insulation

- Switching in vacuum
  - Well-proven in medium voltage
  - Very simple contact system

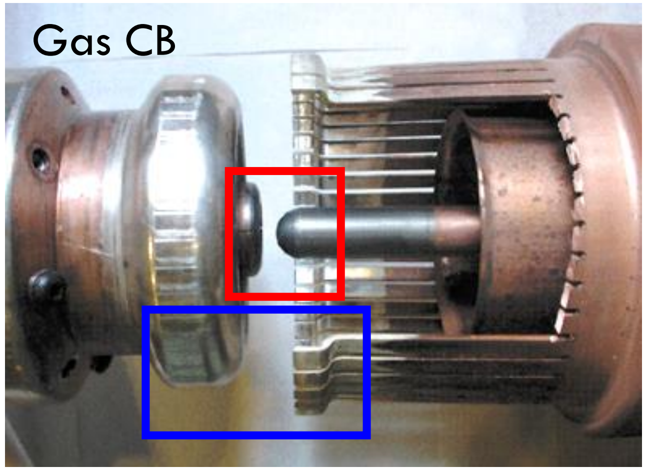
- A single contact system must:
  - Conduct current
  - Interrupt current (incl. fault)
  - Insulate



Siemens Energy



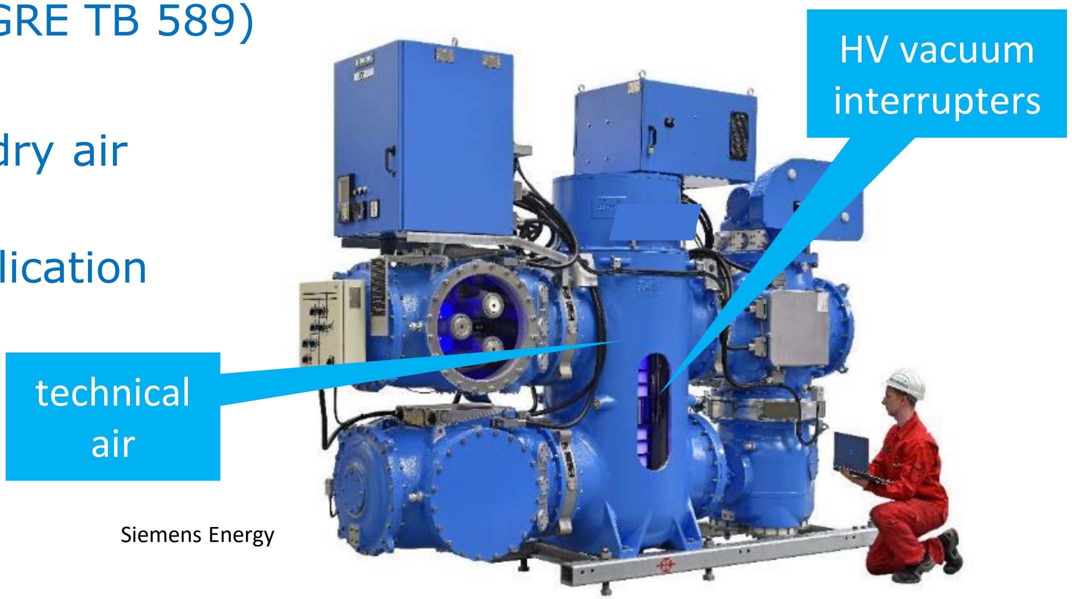
One contact set does it all



main contacts + arcing contacts

- Traditional designs for HV vacuum breakers have SF_6 as insulation
  - Over 10 000 in Japan (CIGRE TB 589)

- New designs use technical/dry air
  - Need higher pressure
  - Very low temperature application

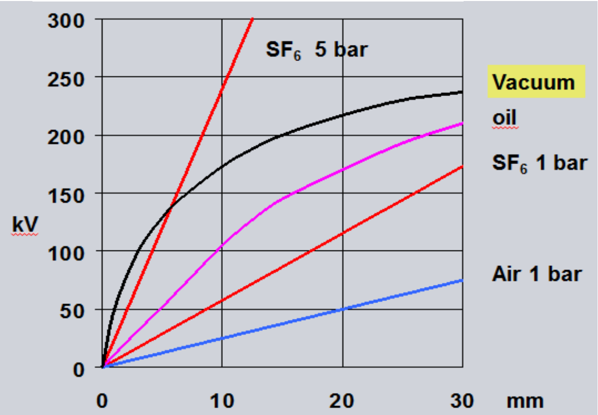


Siemens Energy

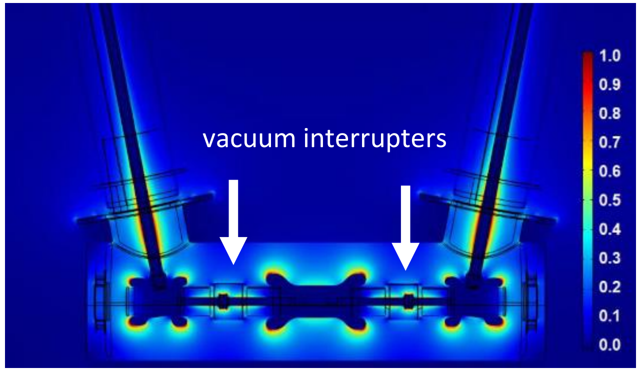
Differences of SF_6-free HV vacuum vs. MV vacuum: steady state

- Natural origin gases as outside insulator has lower critical electrical field
  - Lower breakdown voltage -> higher pressure and/or larger size
- Breakdown voltage not proportional to gap length
  - Increase of gap length no longer effective -> more interrupters in series
- One contact must perform all functions
  - Continuous current for transmission higher -> thermal management
- X-ray emission in open state -> shielding when testing

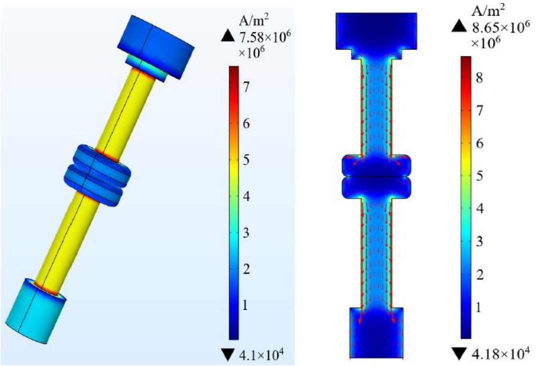
breakdown voltage



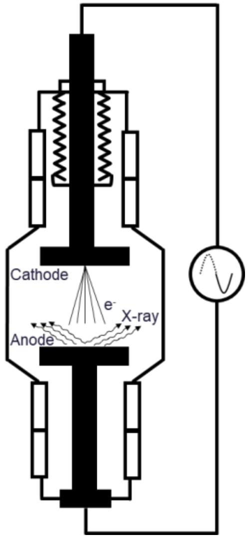
contact-gap length



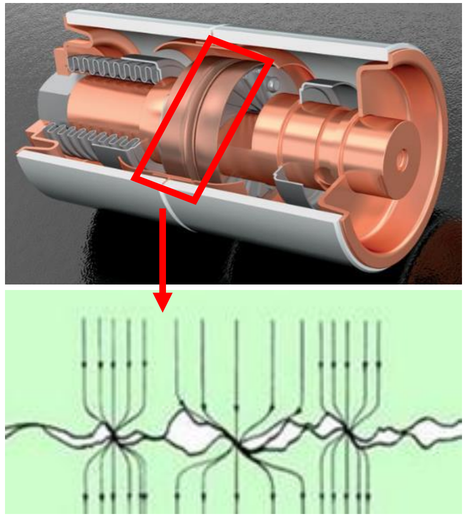
G. Nikolic et al. "Basic aspects of switching with series-connected vacuum interrupter units in high-voltage metal-enclosed and live tank arrangements", CIGRE Conference paper A3-112, 2020



X. Yu et al., "Investigation on the Thermal Performance of a 363 kV Vacuum Circuit Breaker Using a 3D Coupled Model", IEEE Access 2019, D0I1109/ACCESS.2019.2938313



T. Heinz et al., "Why vacuum technology is not a simple scaling from medium to high voltage", ISDEIV 2023

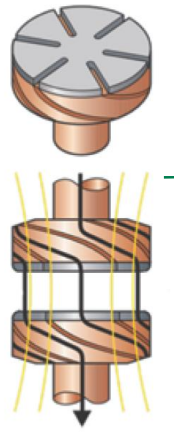


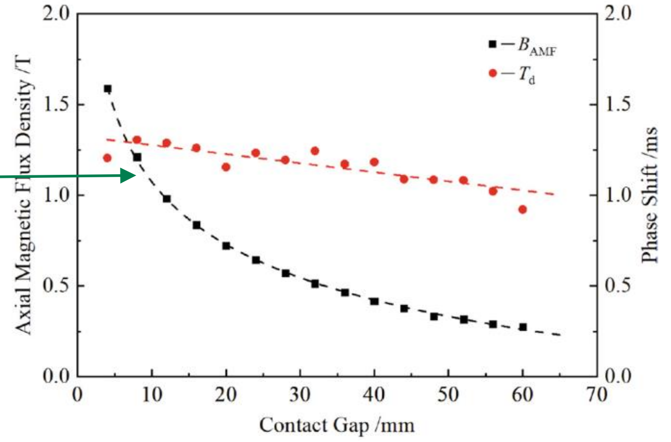
Differences of vacuum vs. SF_6 in current interruption

- Arc control with axial magnetic field becomes challenging
  - Special contact system design
  - May require multi-stage contact separation strategy

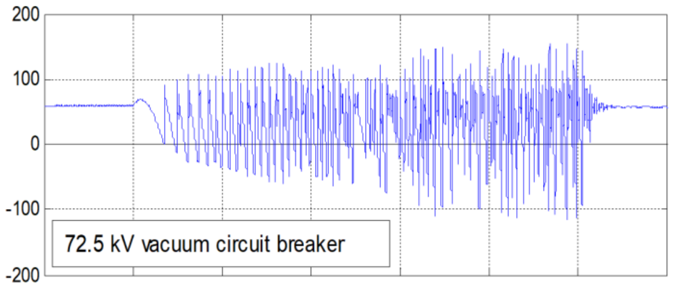
- Post-arc current much larger than in gas-breakers
  - Challenging for voltage grading in series connection

- Transients with inductive/capacitive switching
  - Multiple re-ignitions, restrikes -> mitigation





Z. Liu et al., “Switching Arc Phenomena in Transmission Voltage Level Vacuum Circuit Breakers”, Springer, 2021



R. Smeets et al., “Switching in Electrical T&D Systems”, Wiley, 2014

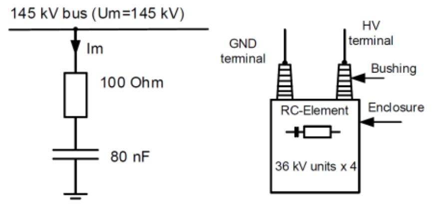
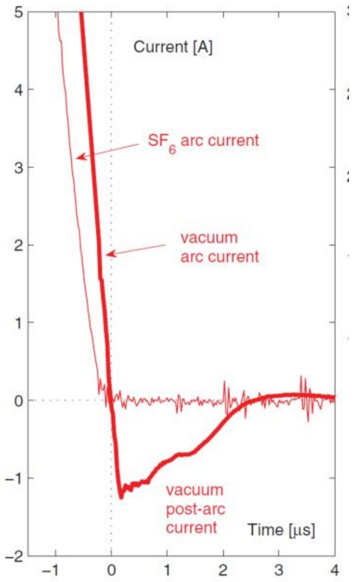
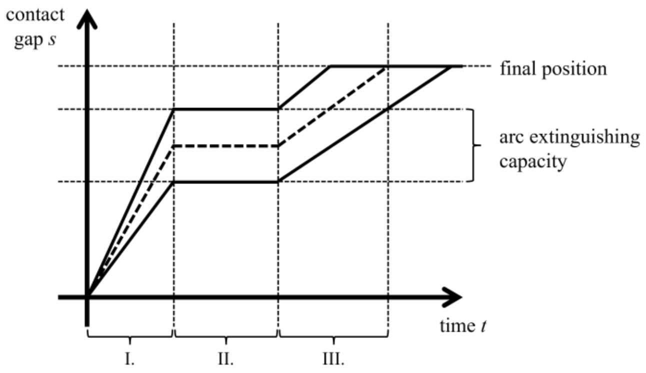


Fig. 7. Rating of RC suppressor for 145 kV system

K. Trunk et al., “Small Inductive Current Switching with High-Voltage Vacuum Circuit Breakers”, ISDEIV conference 2021

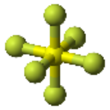
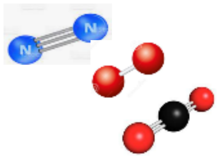
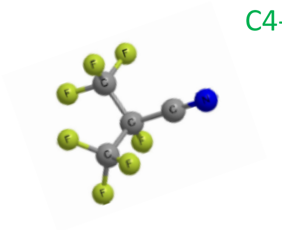


R. Smeets et al., “Switching in Electrical T&D Systems”, Wiley, 2014



T. Heinz et al., “Control of Vacuum Arcs in High-Voltage Vacuum Interrupters by Suitable Stroke Trajectories of Opening AMF Contacts”, ISDEIV 2018

SF_6 – free high-voltage equipment

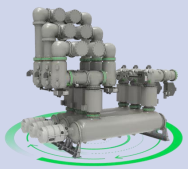
	INSULATION	INTERRUPTION	GWP	VOLTAGE	APPLICATION
 SF_6	SF_6	SF_6	**25 200**	24 – 1 200 kV	dist / LT / DT / GIS
natural-origin gases  N_2 O_2 CO_2	AIR, N_2, solid	VACUUM	0	10 - 170 kV	dist / LT / DT / GIS
	O_2 / CO_2	O_2 / CO_2	1	72.5 - 145 kV	live tank
	TECHNICAL AIR		0	420 kV	GIB / GIL
fluoronitriles	C4-FN / AIR	VACUUM C4-FN / AIR	300 - 750	10 - 40.5 kV	Distr / LBS / GIS
Novec™ 4710	C4-FN / O_2 / CO_2 mixture A	C4-FN / O_2 / CO_2 mixture A	300 - 750	72.5 - 170 kV 420 kV in pilot	GIS live tank dead tank
C4-FN 	C4-FN / O_2 / CO_2 mixture B	C4-FN / O_2 / CO_2 mixture B	300 - 750		
	C4-FN / CO_2	C4-FN / CO_2	300 - 750	170 kV	GIS
	C4-FN / CO_2		> 500	1 000 kV	GIB GIL
	C4-FN / N_2		300 - 750	420 kV	





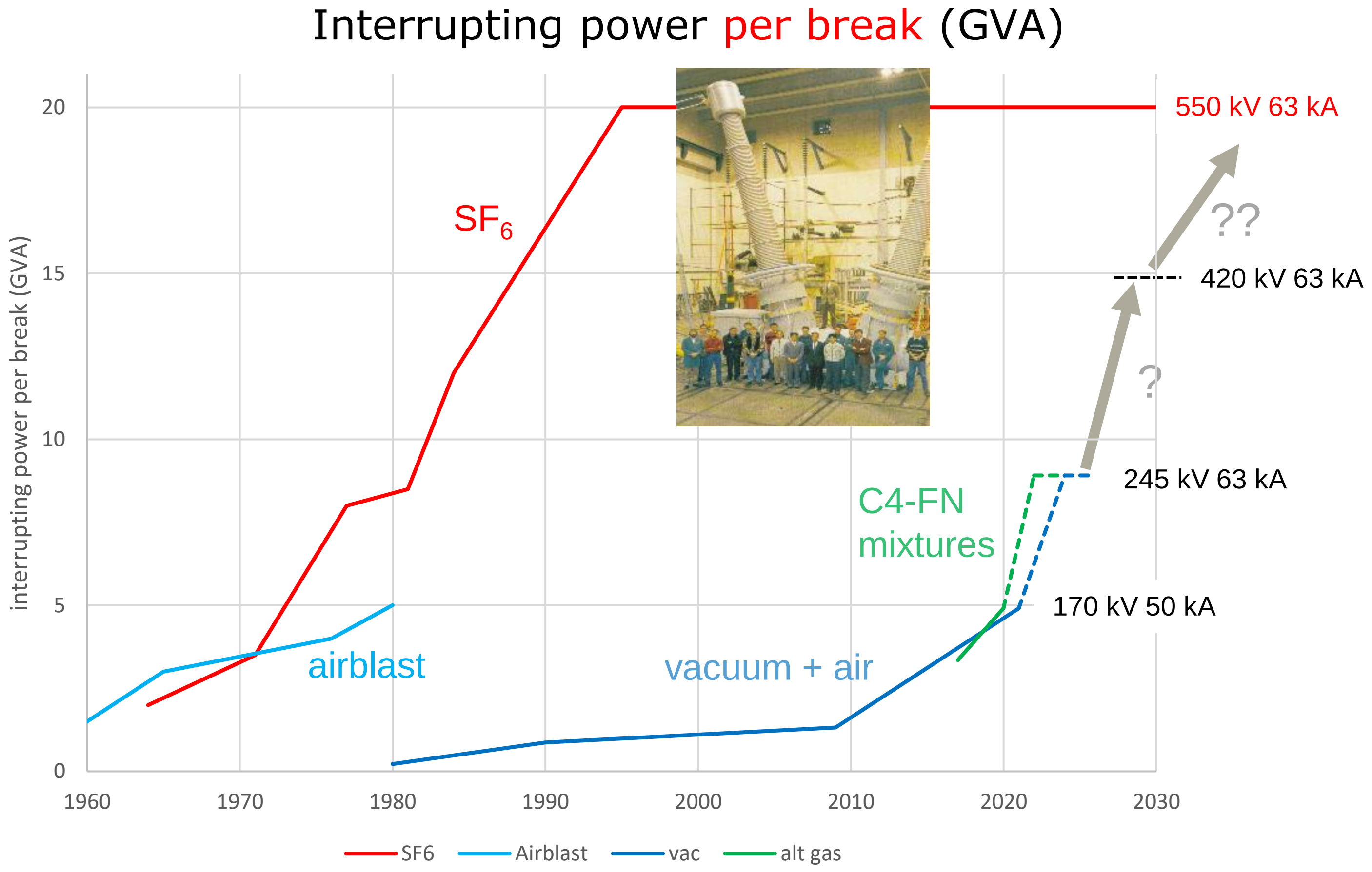


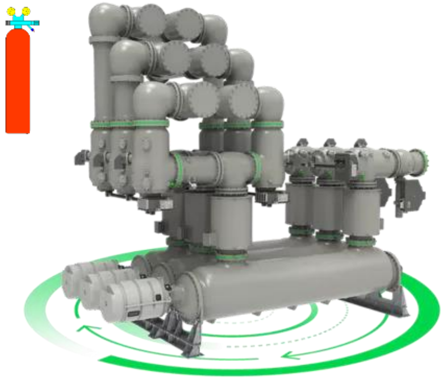
SF_6-free transmission switchgear 72.5 – 420 kV (examples)

	LS IS	GE	Hitachi Energy	Hitachi Energy	HYOSUNG / HYUNDAI	ILJIN	SIEMENS energy	MITSUBISHI ELECTRIC Changes for the Better	비츠로이엠 VITZRO EM	G&W Electric Engineered to order. Built to last.	MEIDEN	TOSHIBA
												
Design	GIS	GIS / LT	GIS	Live tank	GIS	GIS	GIS / LT	Dead tank	GIS	Recloser	Dead tank	GIS
Insulation	C4-FN mix	C4-FN mix	C4-FN mix	Dry air	C4-FN mix O_2-free	Dry air	Techn. air	Techn. air	C4-FN/ CO_2	Solid	Dry air	Dry Air
Switching medium	C4-FN mix	C4-FN mix	C4-FN mix	O_2 / CO_2	C4-FN mix O_2-free	Vacuum	Vacuum	Vacuum	Vacuum	Vacuum	Vacuum	Vacuum
Volt. (kV)	170	145 -> 420	170 -> 420	145	170	170	145	72/84	170	72.5	145	72/84
Current (A)	3150	3150	1250	3150		4000	3150	1200	4000	2000	3150	
SC curr (kA)	50	40	50	40	50	50	40	31.5	50	31.5	40	
Fill. Press. (MPa)abs	0.8	0.85	0.83	1.2	0.85		0.8		0.75	0.8	1.0	-

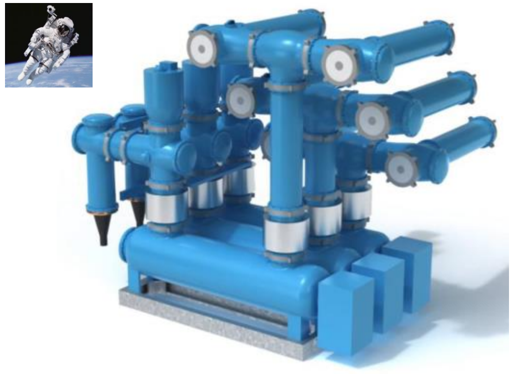
Outlook into SF_6-free switchgear future

- Insulation
  - Gas insulated line / bus already in operation 420 -> 1000 kV
  - Switchgear development lagging (dual gas?)
- Interruption
  - up to 170 kV to approach SF_6
  - (when) can alternatives fully match SF_6?
  - Limit of single break vacuum?
- Multi-break technology
  - Pilots up to 420 kV starting





420 kV C4-FN mixture double break GIS Hitachi Energy 2024



420 kV air insulated+double break vacuum circuit breaker GIS. Siemens Energy > 2025

Status: Where are we now?

- SF_6-free GIS available up to 170 kV, 420 kV announced / in pilot

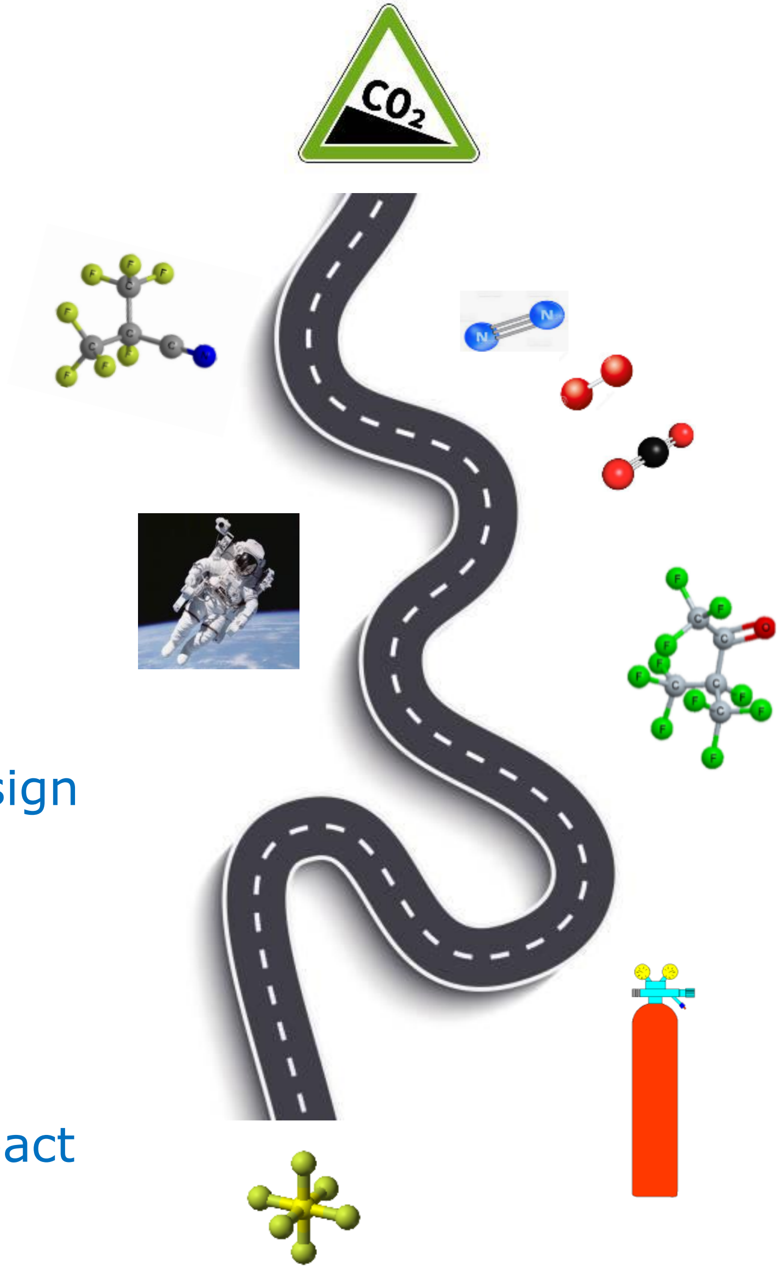
- SF_6-free GIL / GIB in pilot up to 1000 kV

- Three technologies for utility application:

- Mixture of C4-FN with CO_2 / O_2	GWP 300 -750	HV -> EHV
- Vacuum circuit breaker	GWP < 1	MV -> HV
- Mixture of CO_2 / O_2	GWP = 1	HV

- All new media are inferior to SF_6 but this can be overcome by design
  - Higher filling pressure
  - Redesign of key components
  - Acceptance of larger size, weight, cost

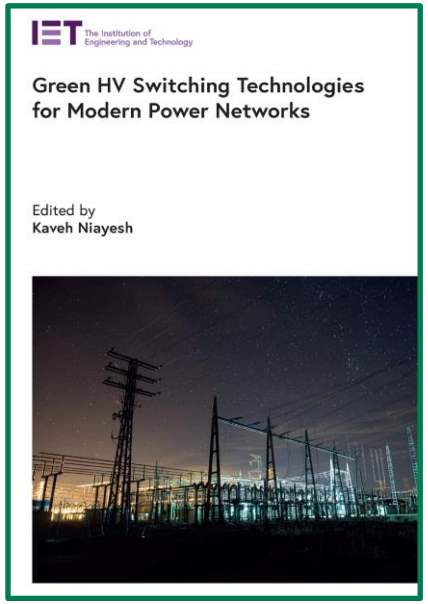
- New EU F-gas prohibitions plus upcoming restrictions on the production of PFAS (per- and polyfluoroalkyl) substances will impact applications in certain markets



Independent industry activities

- **IEEE PES TR64** "Impact of Alternate Gases on Existing IEEE Standards" 2018 (Uzelac)
- **CIGRE WG B3.45** "Application of non-SF6 gases or gas mixtures in medium voltage and high voltage gas-insulated switchgear. TB 802, 2020 (Knol)
- **T&D Europe** "Technical report on alternative to SF6 gas in medium voltage & high voltage electrical equipment", 2020
- **CIGRE WG D1.67** "Dielectric performance of new non-SF6 gases and gas mixtures for gas-insulated systems". TB 849, 2021 (Franck)
- **IEC 62271-4 ED-2** "Handling procedures for gases and gas mixtures for interruption and insulation", 2022
- **CIGRE WG A3.41** "Interruption and switching performance with SF6 free switching equipment". TB 871, 2022 (Smeets)
- **IEEE C37.100.7** "Draft guide for the Evaluation of Performance Characteristics of Non-Sulfur Hexafluoride Insulation and Arc Quenching Media for Switchgear Rated above 1000 V", 2023 (Schiffbauer)
- **CIGRE WG B3/A3.60** "User guide for non-SF_6 gases and gas mixtures in substations" -> 2024 (Knol)

2022, on SF_6 –free switching



2023, on SF_6 alternatives and DC

Thank you for your kind attention!

Next event: CIGRE Paris Conference Monday Aug 26, afternoon:

Workshop "Driving T&D substations and equipment towards zero emissions"

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Nederland

1 February 2024

Towards net-zero emission of T&D grids