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Study Committee A3

Transmission and Distribution Equipment

Paper 10656_2022

Moving Towards Carbon-Neutral High-Voltage Switchgear by Combining Eco-Efficient Technologies

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Hitachi Energy

Motivation

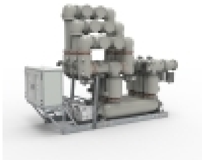
- Reduce the carbon footprint of equipment in the power grid. SF_6 gas losses contribute the major share of equipment's carbon footprint.
- Use an SF_6 alternative that allows to keep the same level of reliability, compactness and scalability that SF_6 technology has.
- Develop eco-efficient switchgear based on SF_6 alternative technology, ensure its acceptance by users and that it quickly becomes a significant fraction of newly installed equipment.
- Address the need of system operators with large installed base to reduce future SF_6 emissions of their equipment.

Method/Approach

- Assess the dielectric and switching performance of key SF_6 alternatives: CO_2/O_2 and N_2/O_2 as well as C4-FN/CO_2/O_2 and C4-FN/N_2/O_2
- Investigate effect the choice of gas on the technical performance (size, scalability) of the equipment
- We identify gas mixtures based on fluoronitrile (C4-FN) as the suitable basis for two key applications to lower carbon footprint

Objects of investigation

- **New equipment eco GIS**: Design of a complete gas-insulated switchgear (GIS) including circuit breakers, disconnectors and fast-acting earthing switches based on a common platform C4-FN/CO_2/O_2 gas mixture.



- **Installed base retrofill**: Gas-insulated lines (GIL) where SF_6 is replaced onsite with a C4-FN/N_2/O_2 gas mixture without changing primary equipment.

Technology development steps

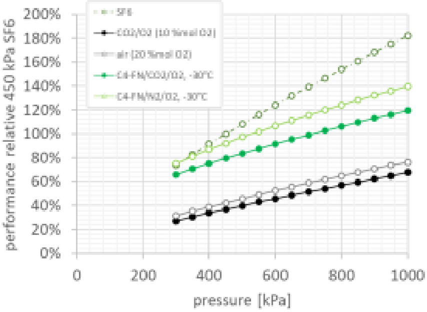
- Based on the two target applications we detail the performed technology development and qualification with a focus on:
    - Materials
    - Health and safety
    - Gas handling
    - Life cycle assessment (impact category global warming)

Dielectric Design

- For compactness, gas-insulated HV equipment uses weakly inhomogeneous fields. Thus, performance comparison of different gases using the concept of SF_6 equivalency is possible. It considers the performance of SF_6-insulation at pressure yielding the same E_{crit}.
- Performance increase by pressure increase: power law with $k = 0.75$ → strong increase in pressure delivers diminishing returns in performance

$$E_w(p) = E_w(p_o)\left(\frac{p}{p_o}\right)^k$$

- Scalability: design limits remain practically the same over all voltage ranges, provided that the production environment and the quality of the manufactured equipment remains similar → SF_6 design rules can be adapted C4-FN/CO_2/O_2 and C4-FN/N_2/O_2
- C4-FN/CO_2/O_2 is optimal for complete eco GIS including switching devices.
- C4-FN/N_2/O_2 is the ideal for retrofill application of passive components, the same dielectric performance as SF_6 can be reached with only minimal pressure increase.



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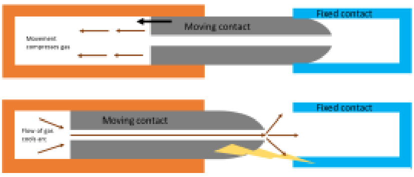
Switching with SF_6 alternatives

- In laboratory studies it was proven, that CO_2-based circuit breakers have significantly better interruption performance than air-based CBs.
- CO_2 and SF_6 differ in their physical properties. The arc zone of a CO_2 or C4-FN/CO_2/O_2 CB can be modified to satisfy the required short-circuit current ratings.
- Non-Circuit breaker switching devices like fast acting earthing switches or disconnectors are an integral part of GIS. For cases like induced current switching with SF_6 alternatives, the introduction of gas flow to cool the arc, together with an increase in the opening speed, significantly enhances the current interruption performance and fulfils the requirements.



- A C4-FN/CO2/O2 based GIS CB for 420 kV is in an advanced development state, together with a fast-acting earthing switch and disconnector-earthing switch for the same voltage rating.

Materials

- Permeation rate is strongly depending on temperature, gas and sealing material.
- For eco GIS based on C4-FN/CO2/O2, a change from EPDM to IIR is required.
- For Retrofill, using C4-FN/N2/O2 a change of sealing material (EPDM) is not required.
- With robust material qualification and selection procedures a complete range of materials for designing C4-FN/CO2/O2 insulated eco GIS was qualified.
- Additionally, for the scope of GIL with C4-FN/N_2/O_2 for retrofill application, we were able to confirm the suitability of the installed material including seals.

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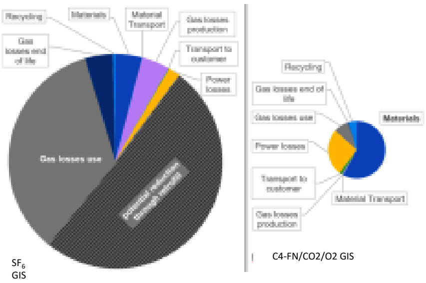
Operational health and safety and gas handling

- The manufacturer provides regional safety data sheets for the C4-FN gas mixtures. The SDS cover all states of the gas mixtures, ranging from “technical grade” to “heavily arced”.
- 3rd party equipment and services are available for all important gas handling steps:
  - gas tightness inspection
  - Gas quality checking
  - Gas monitoring during operation
  - Gas handling during service and maintenance
  - End of Life
- For the gas mixture preparation several options exist: onsite-mixing and offsite mixing. For initial filling, in the overall assessment, onsite mixing is most beneficial. However, the high-voltage equipment itself is compatible with all means to provide the gas.

Life cycle assessment 420 kV GIS



- Main sources for CO_2 equivalent emissions:
  - Gas losses: CO_2 equivalent of insulating gas that escapes to the atmosphere → dominant part for SF_6 technology
  - Grey energy: necessary for material production and transportation
  - Power losses due to Joule heating by operating current
- For equipment with identical ratings, a filling with C4-FN based gas mixtures has 99 % lower CO_2 equivalence than SF_6 → impact of gas losses on LCA is virtually eliminated, Grey energy and power losses are similar as for SF_6 equipment
- C4-FN/CO_2/O_2 is the technology with lowest overall carbon footprint for HV switchgear.
- Retrofill can reduce future SF_6 emissions and significantly lower carbon footprint of the installed base.

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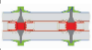
New equipment eco GIS: complete switchgear based on C4-FN/CO2/O2

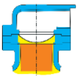
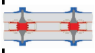
- C4-FN/CO_2/O_2 has excellent performance for insulation (section 2) and interruption
- Low C4-FN content (3.5 mol%) and moderately increased pressure allow low condensation temperature (−30 °C), dielectric performance similar to SF_6 at typical pressures and CO_2 eq reduction of the insulating gas by 99 %
- All equipment in one substation can be filled with the same mixture → easy gas handling
- A complete HV equipment portfolio with ratings from 72.5 kV to 550 kV incl. a GIS for 420 kV with circuit breaker is under development.
- Especially eco-efficient equipment in the transmission level, where large volumes of insulating gas are used, will contribute to efficient reduction of CO2 eq. emissions and allow a fast transition.

Installed Base Retrofill: Gas-insulated Lines Based on C4-FN/N2/O2

- Retrofill addresses the needs of operators of the installed base of SF_6 insulated equipment: they are looking for solutions to avoid either the high write-off cost of early replacement of SF_6 equipment, or the cost of continuing SF_6 management.
- Retrofill of GIL based on C4-FN/N2/O2 allows a lean and fast onsite work procedure with short outtages, avoids future CO_2 emissions and preserves the equipment which as still an economical design life.
- In 2021, the first retrofill was successfully done at an installation in Richborough in the United Kingdom. This is the world's first replacement of SF6 in existing high voltage equipment and 755 kg of SF_6 were removed from approximately 75 m of GIL and replaced with a C4-FN/N_2/O_2 mixture.

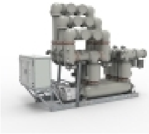
- The SF_6 GIL design in combination with C4-FN/N_2/O_2 gas mixture was fully type tested: Dielectric tests, continuous current test, low and high temperature test and gas tightness test
- Retrofill onsite work procedure:

	 © DILO GmbH	 © DILO GmbH		
SF_6 GIL	Gas quality measurement & no leak confirmation	Reclaim SF6 & Store or disposal of SF6	Exchange density monitor	Exchange gas filling point

	 © Air Liquide / Laurent Lelong	 © DILO GmbH	
Exchange desiccant	Gas mixing and filling	Gas quality measurements	**retrofill C4-FN/N_2/O_2 GIL**

Conclusion

- Eco-efficient solutions for significantly reducing the carbon footprint of HV switchgear can be designed by using C4-FN-based gas mixtures.
- C4-FN/CO_2/O_2 mixtures represent a solution for the full platform of HV switchgear. They have excellent dielectric and arc quenching properties and can lead the way to an industry standard for new equipment.
- C4-FN/CO_2/O_2 enables manufacturers and users to build on decades of experience with SF_6 in dielectric design, gas circuit breaker technology, material choice, operational health and safety and gas handling.



An optimal solution for the installed base using C4-FN/N2/O2 mixtures was developed and implemented to quickly replace large volumes of SF6 in GIL of existing installations and significantly reduce future CO_2 eq emissions.