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Development of SF6 free Clean Air Instrument Transformers and Power VTs

UDO PRUCKER[1)], Detlef Fredrich[2)], Johannes Rickmann[3)], Mana Yazdani[4)],
[1)] Trench Germany, [2)] Siemens Energy China, [3)] Siemens Energy Germany,
[4)] Trench Limited Canada

SUMMARY

As in other industrial areas the reduction of CO_2 emissions is an important focus topic for the electrical power industry and the interest in equipment without or low $C0_2$ emissions is increasing more and more.

SF_6 was used in the past 50 years as insulation and switching medium in GIS as well as HV AIS equipment because of its superior physical properties, especially the excellent insulation and arc quenching capabilities. Due to the high greenhouse potential of SF_6 there are a lot of activities in research and development to find alternative gases with lower greenhouse potential. Currently alternative gases based on Fluor nitriles, Fluor ketones and Clean Air are in use. Whereas the former are still fluorinated gases, which need to be mixed with other gases to avoid liquifying at temperatures below -25 °C, typical for outdoor applications, is the latter industrial air which can be used without liquifying problems even below –50 °C ambient.

The contribution gives an overview about the development status of Clean Air HV Instrument Transformers, like Current-, Voltage- and Combined ITs as well as Clean Air Power VTs. The fundamental technology and dimensioning of Clean Air insulated instrument transformer is shown, that is, design, insulation coordination properties and test results. The Clean Air ITs fulfil the same technical performance as the SF_6 insulated apparatus, with almost identical dimensions and footprint, and fulfil the highest requirements for internal arc resistance up to 80 kA.

In addition to the Clean Air instrument transformers the design of Clean Air Power VTs and Clean Air RC dividers is presented and – as another element of a portfolio with low greenhouse potential – the optical CT with a summary of its measuring principles and design features as a component for the future digital substation.

Various examples for field installations of Clean Air instrument transformers up to 420 kV are presented.

KEYWORDS

Clean Air, SF6 alternatives, SF6 free, zero GWP, fluoronitriles, fluoroketones, instrument transformers, RC-Divider, Power VTs, optical CT

udo.prucker@trench-group.com

1 Motivation

The reduction of greenhouse gas emissions is one of the central topics in the energy industry worldwide. In this context, strong efforts are made to reduce the CO_2 emissions of high-voltage switchgear equipment by removing SF_6 gas to support the transition to net zero emissions and the fight against climate change.

For many TSOs Clean Air Products with zero CO2 emissions are a consistent solution for connecting more renewable energy to achieve the national governmental commitments and targets for net zero emissions.

For the last 50 years, SF_6 has been widely used as an insulating and switching medium in high voltage GIS, circuit breakers and outdoor instrument transformers due to its excellent physical properties, especially its excellent insulation and arc quenching behaviour.

Due to its high global warming potential (GWP) of 23,500 and a lifetime of 3,200 years in the earth's atmosphere [1], the search for more climate-friendly alternative gases to SF_6 is the subject of current research and development activities.

Electrical equipment filled with fluoronitrile, fluoroketones or Clean Air as alternative gases to SF_6 are currently under research and development. While the first two substances mentioned are still fluorinated "gases", Clean Air is synthetic air with a greenhouse potential GWP = 0.

This paper presents the current state of development of blue instrument transformer products e.g., inductive instrument transformers and Power VTS with Clean Air insulation as an alternative to SF_6 insulation to reduce greenhouse gas emissions. Optical current transformers (OCT) and RC-dividers are further products with zero GWP and ready for the digital substation of the future.

2 Properties of Clean Air insulation

Clean Air Gas consists of 80% nitrogen and 20% oxygen [2] and is free of other gases that are otherwise in atmospheric air, as well as free of moisture and hydrocarbons.

Clean Air, i.e., synthetic air, is an industrially produced gas, used for many applications and is available worldwide in 200 and 300 bar cylinders. Only the use as an insulating gas in high-voltage equipment is a new field of application.

In contrast to other alternative gases, Clean Air is completely environmentally and climate-neutral and harmless to humans and animals. Clean Air neither contributes to the greenhouse effect (GWP = 0), nor is it harmful to the ozone layer (ozone depletion potential ODP = 0). In contrast to the classic oil-paper insulation, as it is often used in instrument transformers, Clean Air insulation does not pose any risk of groundwater or soil contamination. Thus, Clean Air devices are ideal for increased environmental protection requirements, such as use in water protection areas.

Life-cycle assessments (LCA) according to ISO 14040 [3] were carried out to evaluate the total CO_2 footprint for Clean Air products. This means an assessment of the CO_2 emissions over the entire product life cycle from manufacture, through operation, to the decommissioning of the product. By using a Clean Air insulated voltage transformer (VT) the CO_2 emissions can be reduced by 62% to 88% depending on service conditions and compared to a state of the art 420 kV SF_6 VT. The expected life-time is 40 years.

The handling of Clean Air gas is also very simple. In contrast to other alternative gases, Clean Air does not have to be mixed with carrier gases as CO_2 or N_2 for use in electrical equipment and can be filled from the gas cylinder directly into the HV-equipment without additional efforts and time-consuming gas handling. For filling of the HV-equipment the Clean Air cylinder is to be connected by a standard armature as for oxygen gas cylinders to the self-closing valve at the instrument transformer similar to SF_6 equipment. In order to avoid filling of Clean Air products with other gases, these valves are equipped with a gas-specific thread.

3 Basic design aspects of Clean Air insulation

3.1 Aspects on insulation and pressure coordination

Clean Air-insulated instrument transformers are based on the same design principles as SF_6-insulated devices and thus show the same basic properties.

The biggest challenge when using Clean Air insulation is the electrical strength, which is 2.5 to 3 times lower than that of SF_6. To compensate for the lower dielectric strength of Clean Air insulation, either an enlarged electrode gap and or a higher gas pressure must be applied.

A larger electrode spacing must be used therefore when applying the same service pressure as for SF_6 equipment, which results in correspondingly larger device dimensions. This concept was followed for the first 123 kV Clean Air combined transformers developed, with a 245 kV SF_6 device serving as the base design (see Chapter 4).

When designing for Clean Air insulation, the different breakdown behaviour to SF_6 must be considered. Paschen's law is not valid and can't be applied for SF_6 and electrical breakdown occurs even within very short distances, immediately after the critical field strength is exceeded. In contrast Paschen´s law is valid for Clean Air as shown in figure 1 and the breakdown voltage of any arbitrary electrode arrangement must be determined along the discharge path applying the Räther criterion [4, 5]. A detailed comparison of the breakdown strength of clean air to SF6 is given in [9]. In order to achieve same housing dimensions and footprint with Clean Air instrument transformers as for SF_6 devices, a filling pressure of 12.5 bar rel. is used which is approx. 2 times higher compared to SF_6.

Another key aspect is the availability of a reliable external potential grading for the instrument transformer bushing. While a grading electrode can be used for lower voltage levels a capacitive grading is more advantageous for current transformers and higher voltage levels as 362 kV and 420 kV. A capacitive grading (condenser) creates a homogenous potential distribution along the exterior of the insulator which finally gives the best field control in respect of the switching impulse behaviour. Additionally, the electric field stress on the silicone surface of the insulator is significantly reduces compared to a grading electrode and using the same insulator diameter.

For a reliable operation of composite-insulators it is important to stay below the critical field stress for water drop corona onset to avoid the loss of hydrophobicity and degradation of the silicone material. The application of a capacitive grading helps to keep the insulator short and small with excellent switching impulse and service behaviour [6]. Due to the different insulation properties compared to SF_6 a capacitive grading design was developed specifically for Clean Air instrument transformers and for voltage levels >300 kV.

In contrast to SF_6 or other alternative gases, Clean Air shows no liquefaction in the relevant pressure and temperature range despite the high filling pressure. As illustrated in figure 2 there is no liquefaction of Clean Air insulation even at high pressures of up to 30 bar and temperatures well below -100°C. Clean Air-insulated instrument transformers can therefore be used in a wide temperature range from -°60 ° C to + 55 ° C without any restrictions to low ambient temperatures that might occur e.g., in Canada and Scandinavia.

For sealing the enclosure, the same proven sealing technology as used in SF_6-insulated devices for decades is applied so that Clean Air devices meet the same leakage rate requirements of 0.5% / a according to IEC 61869 for SF_6-isolated instrument transformers.

The insulation strength which is given by the gas density is monitored using densimeters specially calibrated for Clean Air, which are equipped with switching contacts or an optional analogue current output.

A decisive criterion for the use of gas-insulated instrument transformers is the high operational reliability and operational safety, especially due to the explosion-proof design. With this, the highest protection classes and protection levels for arc fault currents of up to 80kA (r.m.s) are realized (see chapter 3.2).
All parts of the encapsulation of gas-insulated instrument transformers, which are exposed to a pressure greater than 0.5 bar rel. are treated as pressurized parts acc. pressure vessel regulations.

All housing parts of SF_6 and Clean Air instrument transformers are designed according to the same design criteria and pressure vessel standards. The only difference is that they are designed for different service and design pressures. Gas filled instrument transformers are equipped with a rupture disk to prevent bursting of the housing in case of an inadmissible pressure rise, e.g., when filling with too high a pressure or in case of an internal arc fault. Rupture disks are available for a variety of industrial applications with a nominal diameter up to 600mm, response pressure up to 60 bar and a temperature range from -100°C up to 600°C. This easily covers the application and pressure range of SF_6 as well as Clean Air instrument transformers.

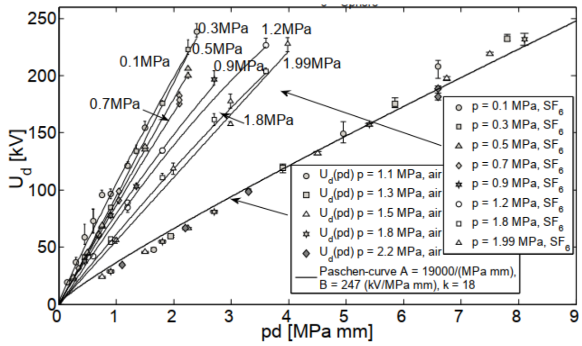

Figure 1: BIL breakdown voltage Ud50 for Clean Air and SF_6 (‘Paschen Curve’) [5]

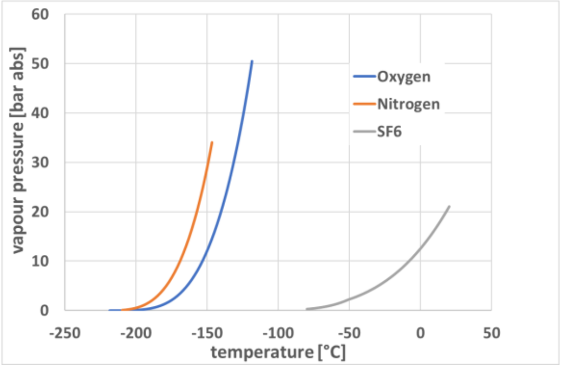

Figure 2: Vapor pressure curves for oxygen and nitrogen as the two components of Clean Air [7]

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3.2 Internal arc fault protection

A decisive advantage of gas-insulated HV instrument transformers is the high level of reliability and security for operating personal and -system due to the explosion proof design in case of an internal arc fault.

In contrast to oil paper insulation the pressure rises much slower and is homogenously distributed inside the enclosure independent where the arc is ignited. The pressure rise is limited by the pressure relief due to operation of the installed rupture disk.

Applying gas insulated technology with explosion proof housing, composite insulator and rupture disk an explosion proof instrument transformer can be realized which fulfils the highest protection classes according to the corresponding IEC and IEEE standards. For Clean Air technology the rupture disk design must be adapted to the higher filling pressure and much faster and higher pressure rise compared to SF_6 gas. The higher and faster pressure rise is related to different gas dynamics and power dissipation of the arc discharge in Clean Air. The internal arc is ignited by a wire which is located at the area of highest field stress as shown in figure 3a. For the specific VT design shown in figure 3b two rupture disks are used which operate simultaneously. The same pressure relief can be realized with only one rupture disk of bigger diameter and same cross section.

Figure 3: a) Ignition arrangement for internal arc test according to IEC 61869-1; b) properly triggered rupture disks for 245 kV Clean Air voltage transformers

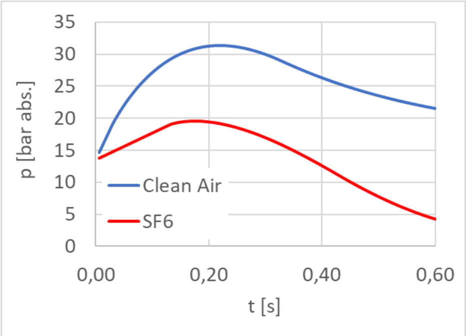

Figure 4: Clean Air vs. SF6. Calculated pressure rise for a 245 kV voltage transformer. Arc current 50 kA, duration 1s, CA filling pressure: 12.5 bar rel, response pressure of the rupture disc: 18 bar rel.

The correct rupture disk design can be done by simulation of the pressure rise behaviour [8]. The maximum pressure of 28 bar abs measured during testing matches very well with the calculated pressure of 31 bar abs as shown by figure 4.

The arc fault resistance has been successfully proven for protection class II and protection stage 2 acc. IEC 61869 also covering IEEE C57.13.5 for the following parameters:

Model	Arc fault current / -duration
Combined transformer 123 kV	40 kA / 300 ms
Voltage / current transformer 245 kV	50 kA / 300 ms
Voltage transformer 420 kV	80 kA / 300 ms

The performed tests also proof that there is no increased fire hazard for Clean Air insulation in case of an internal insulation failure. The fire load from an external fire source is identical to that of SF_6 devices since the same components are used.

4 Clean Air Portfolio and Pilot installations

4.1 Portfolio

The motivation for the development of the first 123 kV Clean Air-insulated instrument transformer was to demonstrate that it is feasible to realize a gas insulated instrument transformers with zero GWP and free of fluorinated gases, but with the same performance as proven SF_6-insulated technology. This was demonstrated by developing a 123 kV combined transformer [10], which was realized using the existing design of a 245 kV SF_6 combined transformer adapted to clean air. Since working with similar service pressure as the SF_6 device the larger electrode spacing of 245 kV must be used. The insulator length was adjusted to the 123 kV voltage level.

While the first 123 kV Clean Air devices represent a "downgraded" SF_6 devices, the subsequent developed 245 and 420 kV voltage transformer as well as the recently tested 245 kV CT were specifically designed for Clean Air insulation, i.e., for a higher service pressure and with very similar dimensions and same footprint as SF_6 designs (see figure 5). 420 kV current- and combined transformers and the next generation of 123/ 145 kV instrument transformers optimized for Clean Air insulation are currently under development.

Figure 5: Comparison of Clean Air (blue) und SF_6 (green) voltage transformers) 420 kV b) 245 kV

Figure 6: Basic Power VT (PVT) design

All Clean Air Instrument Transformers developed have been type-tested in accordance with IEC 61869.

There are no restrictions of the tested Clean Air ITs compared to corresponding SF_6 units with regards to the technical parameters, such as operation temperature range, rated current, short-circuit current, lightning impulse including CW, as well as the mechanical loads.

Because of the new clean air insulation medium, the devices were also subjected to an internal arc test with up to 80 kA as a special test.

Table 1 gives an overview of the most important technical parameters of the tested devices:

Table 1: Electrical parameters of the developed Clean Air combined transformers (combi), current transformers (CT) and voltage transformers (VT)

	Combined 123 kV	**CT 123 kV**	**VT 245 kV**	**CT 245 kV**	**VT 420 kV**
AC [kV]	230	230	460	460	630
BIL [kV]	550	550	1050	1050	1425
CW [kV]	630	630	1200	1200	1640
SIL [kV]	-	-	-	-	1050
Ir [A]	4000	4000	-	4000	-
Ith [kA]	40	40	50*	50	80*

*current through terminals

AC: Rated power-frequency withstand voltage (rms) BIL: Rated lightning impulse withstand voltage (peak)
CW: Chopped wave withstand voltage SIL: Rated switching withstand voltage (peak)

The experiences gained during Clean Air voltage transformer development have also been applied to the Power VT (PVT) portfolio. PVTs represent a special kind of instrument transformers, which are designed to provide an output power in the range of 100 kVA at the secondary low-voltage side with a secondary voltage of typically a few 100 V.

PVTs are well known in North America and are mainly used as auxiliary power supply for switchgears, which is why they are also known as Station Service Voltage Transformer (SSVT). Since the PVT design is related to that of a voltage transformer (see figure 6) the PVT design will be covered by a common IEC and IEEE standard which is currently under preparation and is provided by the corresponding instrument transformer committees.

The new developed Clean Air VT components as insulator and bushing with potential grading were used to realize a blue PVT portfolio in Clean Air technology.
So far Clean Air PVTs have been developed up to 420 kV, successfully type tested and available for 25, 50, 100, 167 kVA power ratings.

Other applications for Clean Air are gas insulated Low Power Instrument Transformer (LPIT) on the principle of an RC dividers for AC and DC application and optical current transformers with digital signal output. These LPITs (RC dividers) consist of capacitors and resistors connected in parallel building modules connected in series for the high voltage part and the low voltage part consists of a capacitor and resistor connected in parallel, with the high voltage part housed in a composite insulator. Figure 7 shows a schematic diagram of an RC divider.

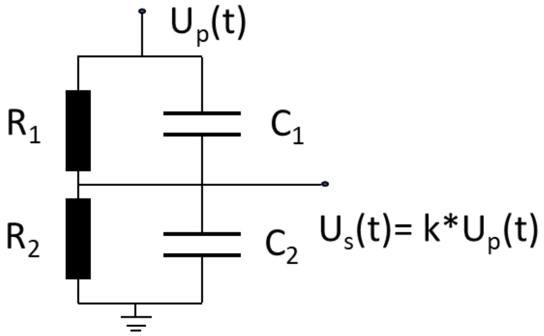

Figure 7: Schematic diagram of an RC divider

Figure 8: RC 500 VG during seismic test

The all-film capacitors are built into an FRP tube and insulated with gas. These capacitor modules with the parallel connected resistors can be connected in series, depending on voltage class between 100 kV and 800 kV. The modules are placed in an FRP insulator which is also filled with gas.

This technology has a proven operation record under SF_6 gas since 2000, but in 2011 500 kV DC dividers with an alternative gas were required for an HVDC connection between Denmark and Norway. The main parameters are 500 kV rated DC voltage, 1282 kV BIL, 1014 kV SIL with 2 mA rated primary current. Extensive research showed that the capacitors could also be built with N_2 and Clean Air insulation at the same pressure as under SF6. Also, the pressure for the main housing insulator could be kept the same, eliminating the need for thicker insulators which would have been necessary in case of a pressure increase. This was possible since the main insulation between the capacitor electrodes is provided by the polypropylene film and the gas is used to increase the insulation strength around the connections. The results of the N_2 insulated RC divider can be transferred to Clean Air, since Clean Air has a minimum insulation advantage over N_2 of 7% at negative Lightning Impulse voltage [9].

The dividers are now successfully in service since 2013.

Optical CTs measure electrical currents by application of the Faraday effect, a magneto-optic phenomena describing the interaction of light with magnetic fields. Optical current sensors can be built completely from insulating materials like, amongst others, glass, ceramics and plastics. Optical current measurement is beneficially applied for high-voltage networks up to 800 kV. As a result, optical CTs can be small and compact in design even in the highest voltage ranges. However, "classical" specifications in mechanical loads for such instrument transformers still define a certain minimum size for the devices. Also, optical CTs are environmentally friendly as their, compared to "classical" instrument transformers, simplified insulation system applies clean air or nitrogen only instead of SF6 or mineral oil.
The components of an Optical CT are shown in figure 9. Optical CTs are by design saturation-free, and have a wide dynamic range and high bandwidth, basically only limited by the signal electronics and the secondary interfaces. Standardization through IEC 61850 and IEC 61869 series will help to introduce optical CT in high-voltage networks (figure 10) and digital substations in the near future.

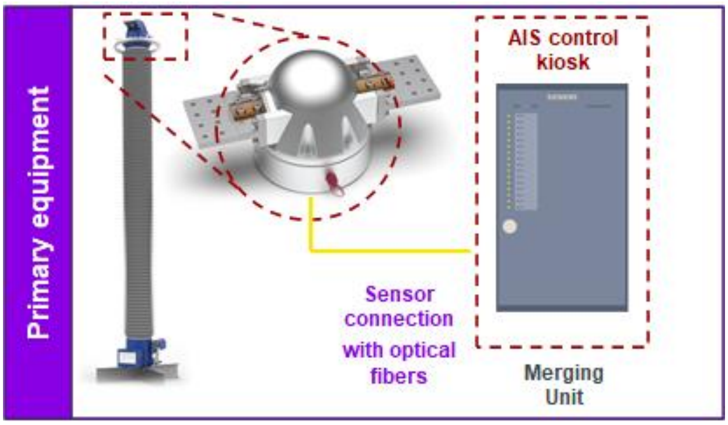

Figure 9: OCT components

Figure 10: 245 kV OCT installation

4.2 Pilot Installations and Experience

Meanwhile more than 400 Clean Air-insulated products had been delivered for and out of pilot installations gathering more than 100 years of service experience without failure. An important milestone was the worldwide first Clean Air installation in the AIS substation Nördlingen (Germany) (see figure 11). Due to the strong increase in renewable energy, it was necessary to extend the 110 kV/20 kV substation. Since sustainability and environmental protection are firmly anchored in their corporate policies Netze BW and the local partner Netze NGO decided to equip two of the renewed 110 kV air-insulated feeders with SF_6-free technology, that means high voltage vacuum circuit breakers and Clean Air insulated combined instrument transformers. The feeder bays had been put into service in June 2018 and have now been in operation for more than 3 years [10, 11].

Figure 11: First pilot installation of 123 kV clean air combi transformers in substation Nördlingen (Germany)

Figure 12: 145 kV SF_6 free switchgear in Fårhult (Schweden)

Since 2019 EON Energidistribution AB Schweden has 145 kV CO_2 free Clean Air current- and voltage transformer in service for the Fårhult substation (figure 12). Due to an environmental friendly company policy at E.ON and the low ambient temperature conditions at -50°C in some parts of the E.ON regional grid in Sweden, the company decided to start pilot installations with clean air insulated blue instrument transformers to reduce the CO_2 footprint in their substations [12]. Same maintenance and handling capability like other insulation types as well as easy gas handling without using gas mixtures is seen as an advantage.

In parallel to the 145 kV installations first pilots for 245 kV and 420 kV followed with first deliveries of 245 kV Clean Air voltage transformers in 2017 and of 420 kV voltage transformers in 2019 for the German TSOs TenneT and Amprion (see fig. 13). All these units had been successfully installed, commissioned and are in fault free service since installation.

Besides the installations in Europe there are also installations and orders realized for the US meanwhile, e.g., 6 units of 362 kV voltage transformers in Texas and 96 units of 72.5 kV combined transformers in Pennsylvania.

Figure 13: 420 kV clean air voltage transformer installed in TenneT TSO grid.

Figure 14: 145 kV, 50kVA clean air Power VTs at Glen Kyllachy substation at SSEN Transmission for connecting a windfarm.

The first clean air Power VT installations was installed at Glen Kyllachy substation of the Scottish&Southern Electricity Networks (SSEN) Scotland (fig. 14). The Glen Kyllachy wind farm connection was energized in May 2021 and connected to the national grid through a new substation equipped with 145 kV Clean Air Power VTs. SSEN sees their role not only in connecting clean green energy but also to tackle responsibility for their own emissions by employing innovative technology in every aspect of their operations. [13].

"The installation and energisation of Siemen's Clean Air Power Voltage Transformers at Glen Kyllachy substation, yet another first, is a clear demonstration of SSEN Transmission's Science Based Target commitment in action, as it continues to deliver a Network for net zero" [13].

5 Conclusion

The CO_2 emission of gas insulated instrument transformers can be reduced significantly when using Clean air instead of SF_6. Clean Air instrument transformers operate with a higher service pressure to compensate for the lower dielectric strength and to achieve the same footprint as SF_6 devises. Clean Air ITs are based on the same basic design as SF_6 units, have the same service performance, can be used down to -60°C without restrictions and are explosion proof.

Clean Air inductive instrument transformers are available as Power VTs, current-, voltage- and combined transformers. RC-dividers and optical current transformers with digital interface and Clean Air insulation are also available. The products presented were developed, type-tested and installed up to 420 kV voltage level. Various installations and more than 100 years of service experience with Clean Air insulated instrument transformers up to 420 kV are available.

BIBLIOGRAPHY

[1] G. Myhre et. al, "Climate Change 2013: The Physical Science Basis, Fifth Assessment Report", Intergovernmental Panel on Climate Change. 30. September 2013.

[2] Safety data sheet acc. RL 1907/2006/ EG (Reach) Alphagas 1 Luft 203001_01.

[3] "Environmental management – Life cylcle assessment – Principles and framework", ISO 14040, 2006.

[4] A. Hopf, F. Berger, M. Rossner, "Die Berechnung der elektrischen Festigkeit, Anfangsfeldstärke und Durchschlagsspannung von SF_6 und synthetischer Luft hei hohem Druck im schwach inhomogenen Feld", Berlin, VDE-Hochspannungstechnik 2018.

[5] A. Hopf, M, Rossner, F. Berger, U. Prucker, "Dielectric strength of alternative insulation gases at high pressure in the homogeneous electric field", IEEE Seattle, 2015.

[6] U. Prucker, "An improved condenser grading for SF6 insulated high voltage apparatus", XIIth ISH, Bangalore, 2001.

[7] "Echte Werte: Technische Gase in Zahlen, Daten und Fakten", Westfalen AG, A2 0711 3T, http://www.westfalen-austria.at/fileadmin/user_uploads/Westfalen_AG/Technische_Gase/Allgemein/Prospekte_Technische_Gase/Echte_Werte_Zahlen.pdf

[8] J. Oberthür, "Dimensionierung von Druckentlastungseinrichtungen in SF_6-isolierten Anlagen", ELEKTRIE 40, 1986, pp. 92-94.

[9] Cigre Brochure 730: Dry Air_N2_CO2 and N2-SF6 Mixtures for Gas-Insulated Systems

[10] T. Heinz, D. Helbig, J. Teichmann, S. Wethekam, U. Prucker, M. Konermann, M. Engel, C. Wolf: "145 kV Vacuum Circuit Breaker and Clean Air Instrument Transformer – Performance, Installation- and Operational Experience", VDE-Hochspannungstechnik, Berlin, 2018.

[11] https://press.siemens.com/global/de/feature/weltpremiere-noerdlingen-offizielle-inbetriebnahme-der-ersten-sf6-freien-schaltgeraete-im?content[]=EM

[12] "Siemens to supply SF6-free high-voltage products for E.ON in Sweden", NS Energie 20 Nov. 2018.
https://www.nsenergybusiness.com/news/siemens-high-voltage-products-sweden/

[13] "Greener grid at Glen Kyllachy", Scottish&Southern Electricity Networks Transmission, 21 May2021, https://www.ssen-transmission.co.uk/news-views/articles/2021/5/greener-grid-at-glen-kyllachy/