SF6 FREE ALTERNATIVE – STUDY OF TERNARY MIX NATURAL GAS FOR ELETRICAL INSULATION PURPOSE

Paper No. PCIC energy EUR23_22

Luigi Bellofatto
luigi.bellofatto@imesaspa.com
Imesa S.p.a.
Via G.di Vittorio 14 Jesi
Italy

Pietro Sigismondi
pietro.sigismondi@imesaspa.com
Imesa S.p.a.
Via G.di Vittorio 14 Jesi
Italy

Abstract - SF6 gas has been used for insulation and breaking current in medium voltage switchgear for the past decades. The reasons were related to his long-time stability and exceptional electrical properties for switchgear applications that let the industry develop all the product using only type of gas, the best cost-effective insulation material. Currently, due to its very high global warming effects and high costs of recycling and end of life management, the manufacturers are looking for something new that has to be “SF6 free”, according to new latest technologies. The goal of this project is to analyse dielectric performance of ternary origin natural gases mix (N_2+CO_2+O_2) used as insulator in a medium voltage electrical switch, according to the standard reference. This mix has intrinsically zero impact for the environment.

I. INTRODUCTION

SF_6 is a colourless, odourless, non-toxic, non-flammable, and non-reactive gas under normal environmental conditions. It is also dense, about five times heavier than air. Due to its excellent insulation and arc quenching properties, it is widely used across electrical utilities, from large power stations, wind turbines, to electrical sub-stations in towns and cities, both in medium and high voltage applications. It has been in use in electrical equipment since the 1960’s, with a current consumption of about 80% of the whole gas production. Although it presents many advantages in terms of technical properties, SF6 has the disadvantage of having the highest global warming potential (GWP) among greenhouse gases (GHG). Moreover, its extensive longevity in the atmosphere induces an increase of its GWP with the time horizon. While its current effect might be considered marginal versus carbon dioxide (CO2) according to the total quantity into atmosphere, its 3200 years lifetime in the atmosphere makes it a legacy we must stop accumulating as quickly as possible (see Table 1)

Greenhouse Gases	GWP 20 years horizon	GWP 100 years horizon	GWP 500 years horizon	Atmospheric Lifetime (Years)
Carbon dioxide (CO2)	1	1	1	Variable
Methane (CH4)	72	25	7,6	12
Nitrous oxide (N2O)	289	298	153	114
Nitrogen trifluoride (NF3)	12300	17200	20700	740
Sulphur hexafluoride (SF6)	16300	22800	32600	3200

Table 1: GWP greenhouse gases

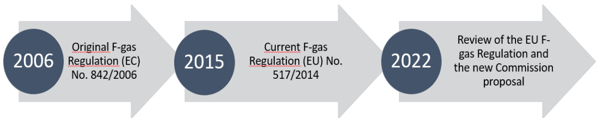
The most important means by which SF6 gets into the atmosphere is from the leakage from electrical apparatus equipment during its entire life span. Over the last two decades, the industry has made significant progress in reducing SF6 leakage rates and handling losses because of a better understanding of the best practices and most suitable technologies for managing SF6.
According to IEC international standards, the leakages in operation for MV switchgear are 0.1% per year while indeed the end-of-life leakages are very uncertain. Since SF6 must be either recycled or destroyed, either by the gas producer or a specialized service provider, end-of-life handling of the MV switchgear during decommissioning has a key role in their lifetime emission. There is a wide gap between industry best practices of about 1.5% end-of-life leakages and the worst-case assumption of about 40% end-of-life leakages for mainly uncontrolled end-of-life handling.

ELECTRICAL SWITCHGEAR DEVELOPMENT TECHNOLOGY

There are three main technical solution/technology used in switchgear design:
Air-Insulated Switchgear: is commonly used and is well-accepted because of its flexibility of configuration and long history of use. It uses ambient air as an insulation medium in a metal-clad or metal-enclosed housing. For this reason, it is susceptible to local environmental conditions such as humidity, corrosive substances, dust, and salty air, which are all contributing factors to switchgear failure over time. Also, due to the low dielectric withstanding of ambient air, the dimensions of the AIS become larger at higher voltage levels limiting

their use when access to space or cost of land is a significant factor.
SF6 Gas-Insulated Switchgear: due to its high dielectric withstanding properties, SF6 has enabled the development of very compact gas-insulated switchgear (GIS). For several reasons, these have become widely adopted: smaller footprint, low total cost of ownership (TCO) due to, reduced maintenance requirements, greater safety due to no exposed live parts and higher reliability. However, SF6 is a greenhouse gas with an extremely high GWP so the broad industry has been seeking alternatives to maintain the benefits of GIS.
SF6-Free Gas-Insulated Switchgear (still under development): in its use of alternative gases to SF6, maintains the advantages of traditional GIS that operators have become used to without the environmental harm associated with SF6. The use of alternative gases as an insulation medium, with generally lower dielectric withstand capabilities as compared to SF6, means that SF6-free switchgear would have to be designed to compensate for these differences. The alternative gases may need to operate under higher pressures to improve their dielectric performance. Such change would require more steel and other materials in the gas vessel construction to be considered because the mass of any material with carbon footprint may vary for different switchgear technologies.

CURRENT ROADMAP EU REGULATION F-GASES



The current Regulation (EU) No.517/2014 [1] strengthened the previous measures and introduced far-reaching changes by:
- limiting the total amount of the most important F-gases (HFCs) that can be sold in the EU from 2015 onwards and phasing them down in steps to one-fifth of 2014 sales in 2030. This will be the main driver of the move towards more climate-friendly technologies
- banning the use of F-gases in many new types of equipment where less harmful alternatives are widely available, such as fridges in homes or supermarkets, air conditioning, foams and asthma sprays
- preventing emissions of F-gases from existing equipment by requiring checks, proper servicing and recovery of the gases at the end of the equipment's life

Thanks to this, the EU's F-gas emissions will be cut by two-thirds by 2030 compared to 2014 levels.
This regulation is currently under review from 2022 by a new European Commission preparing for phase out of SF6. It should be banned from most new electrical equipment as early as 2026 for switchgear up to 24kV and for higher voltages by 2031.

The current EU's F-gas review is intended to:
- deliver higher ambition e.g. through a tighter quota system for HFCs (HFC phase-down): reduce the amount of HFCs placed on the market by 98% by 2050 (compared to 2015). New restrictions on the use of F-gases in equipment are also included
- ensure compliance with the Montreal Protocol, e.g.. making phase-down steps also after 2030 and ending certain exemptions to the EU's HFC phase-down that do not exist under the Montreal Protocol
- improve enforcement and implementation, e.g.. by making it easier for customs and surveillance authorities to control imports and exports. A quota price will be introduced, and penalties will become harsher and more homogenous across the EU
- achieve more comprehensive monitoring, e.g.. by covering a broader range of substances and activities and improving the procedures for reporting and verifying data

STUDY OF POSSIBLE ALTERNATIVE

Identification of viable alternatives to SF6 is complicated by the unique combination of properties required in dielectric applications. Unfortunately, the very properties that make SF6 an ideal insulating gas, namely chemical inertness, are the same properties that make it exceptionally long lived in the atmosphere. Therefore, any replacement of SF6 as an insulating gas must implicitly have some form of reactivity to facilitate degradation in the atmosphere and overcome the environmental concerns. The materials also need to be non-flammable and low enough in toxicity to allow for safe handling using practices similar to those currently used within the industry. Alternatives certainly need to have very high dielectric strength, providing performance as close to SF6 as possible. Since the gas-filled also be stable over the working life of this equipment without contributing to corrosion or other adverse effects on the device. Most importantly, to be sustainable alternatives, new compounds need to have acceptable combinations of environmental properties, including no ozone depletion potential and significantly reduce the greenhouse gas emissions from these applications compared to SF6, since this is the principal reason for transitioning to new technology. Two compounds, a fluoronitrile C4 and a fluoroketone C5, were found to combine the required properties for electric power applications [2]. They both have been shown to function as a key dielectric component in insulating gas mixtures while providing significantly lower climate impact. As a result, the electric power industry has begun implementing SF6-alternative gas mixtures based upon these compounds over the last several years [3]. Different studies and researches have been done for analysing performance and behaviour and good results have been achieved both for apparatus and switchgear in medium and high voltage field. Some companies developed and invested in F-gas alternative technology and products based on these 2 compounded gases, taking care of all the key aspects during the lifetime (GWP < 10, safety, handling, toxicity, non-flammability, material compatibility, ageing, electrical performance under different conditions, end of life) completing the requested certification according to the standards and in some cases installing on field the new products. This seemed to be the right path for the free Sf6 transition, with the most companies that defined a clear R&D roadmap and investment as business target over the next years. But the scenario has recently completely changed after the European Parliament would be largely banned the production and use of forever chemical under a proposal issued published on Tuesday 7th of February 2023 by the ECHA (European Chemicals Agency) [4]. Ongoing consultations on conforming restriction proposals are currently under consideration. The ban, which will affect about 10,000 per- and polyfluoroalkyl substances (PFAS), will hit multiple economic activities and leave companies searching for alternatives for their products and production processes. The ban will also extend to imports to the EU of products containing PFAS. The PFAS prohibition would be phased in through the late 2030s as derogations for some uses of PFAS run out.

According to that, the technical development scenario has completely changed. The most promising gases C4 and C5 that a lot of companies were starting to use will not be available anymore. So, for the companies there is currently the urgent need to re-define R&D roadmap and re-design some products. Now is ongoing a step back about the possibility to use natural origin gases, that is the best solution for achieve the net zero grid.

Consequently, the scope of the project has changed analysing the possibility to use, as SF6 free alternative, a basic compound of natural origin gases like O2, N2, CO2. It is clear from the beginning that there won't be a mix able to replace SF6 electrical performances, but the aim is to find the best compromise in term of dielectric performance for replacing it as gas insulation. The gap between SF6 and this mixture has to be closed through a different design of the products, that means unavoidably cost increasing.

ANALYSIS IN DIELECTRIC STRENGHT OF O2, N2, CO2 TERNARY MIXTURE

These gases, which are abundant in nature, are chemically and thermally stable despite their relatively low dielectric strength compared to SF6. Noble gases are used as a buffer gas in binary gas mixtures with high dielectric strength such as SF6. CO2, N2 and O2 can be used in medium-voltage GIS equipment with high-pressure designs. Currently, GIS and circuit breakers designed with high pressure CO2 are commercially operating at voltage levels of 72.5 and 145 kV. The relative dielectric strengths of CO2, N2 and O2 gases with respect to SF6 are 0.44–0.50, 0.37–0.40 and 0.33–0.37, respectively. Despite this relatively low dielectric strength, these non-synthetic alternatives have significant advantages such as low GWP values, lower boiling temperatures, low cost effective and non-toxicity. Although these gases have close dielectric strengths with each other, they have different characteristics in terms of thermal interruption capacity and synergistic effects. This study aims to investigate the overall dielectric performance of the ternary gas mixture of CO2, N2 and O2 gases filling a rotative disconnector with this mixture (24kV rated voltage filled with SF6) applying an AC lighting voltage impulse (according to [6] IEC 62271-102 standard). Finding the best mixture for buffering gases and the optimal ratio of them is very important. For dielectric strength of a gas mixture, the synergistic effect is usually used to evaluate and optimize the choice of gases in the mixture, the mixed ratio, and the gas pressure. In this context, the synergistic effect leads to a dielectric strength of a mixture of ternary gases being greater than the linear interpolation of the dielectric strengths of the three isolated gases. This nonlinear synergy effect can be calculated by the following empirical formula proposed in a previous paper for the binary gas mixture [7]:

$$Vm = V_2 + \frac{k\,(V_1 - V_2)}{[k + (1 - k)\,C]} \qquad V_1 > V_2$$

where V_1, V_2 and V_m are breakdown voltage of pure gases and gas mixture, is the mixing ratio and C is the synergy effect constant. The smaller the C value, the stronger the synergy effect is observed. With the increase of this value, the synergistic effect decreases and the breakdown voltage characteristic between V1 and V2 gases changes linearly according to the mixing ratio. The Eq. 1 can be rearranged based on C constant,

$$C = \frac{k\,(V_1 - V_m)}{(V_m - V2)\,(1 - k\,)} = \frac{kV_1\,(V_1 - V_m)}{kV2\,(V_m - V_2)}$$

where kV1 and kV1 are the ratio of gases 1 and 2 in the mixture, respectively. As can be easily seen in Eq. 2, the synergy effect is the ratio of the weighted effects of the gases on the breakdown stress of the mixture. Using this approach, the C constant for CO2+N2+O2 ternary mixtures can be calculated with the following equation:

$$C = \frac{kO_2\,(VO_2 - V_m)}{kCO_2\,(V_m - VCO_2) + KN_2\,(V_m - VN_2)}$$

Equation 3 can also be written with the number density reduced limiting electric field instead of the breakdown voltage V:

$$C = \frac{kO_2\left(\frac{E}{N\ limit\ O_2} - \frac{E}{N\ limit\ m}\right)}{kCO_2\left(\frac{E}{N\ limit\ m} - \frac{E}{N\ limit\ CO_2}\right) + kN_2\left(\frac{E}{N\ limit\ m} - \frac{E}{N\ limit\ N_2}\right)}$$

where the effect is the number density reduced limiting electric field (E/N) lim, corresponding to the case in which ionization frequency is balanced by attachment frequency in electronegative gas mixtures (E is the applied field magnitude and N is the number density of gas molecules). A dielectric gas breakdown voltage (the voltage necessary to start a discharge or electric arc) in a homogenous field is controlled by the generation and disappearance of free electrons. Paschen's law is an equation that describes the breakdown voltage between two electrodes in a gas as a function of the gas pressure (*p*) and the distance between the electrodes (*d*). Paschen curves, which plot the DC breakdown voltage vs. the product of the gas pressure times the gap distance (*pd*), illustrate that the voltage is dependent on *pd*. The present project focuses on the conditions of relatively large *pd* products where Paschen's law applies (characteristic of the Paschen curve changes approximately linearly), that means the increase of pressure has a positive effect on the dielectric strength. To examine the discharge behaviour of the CO2+N2+O2 ternary mixtures, the component gases are mixed by adjusting their partial pressure ratios.

EXPERIMENTAL ARRANGEMENT AND PROCEDURE

The experiment circuit is presented in Fig. 1. This contains a main control desk (HV 9103) which has built-in variable voltage supply and peak voltmeter (HV 9150). The output of supply is 0–230 V and range of peak voltmeter is 100–1000 kV. Test transformer (HV 9105) output is 220 V–100 kV in a single stage, 200 kV in two stages and resistor is connected for protecting test transformer during the breakdown. The breakdown as it occurs, its voltage is measured by the voltmeter through measuring capacitor. Before starting the experiment, voltmeter and measuring devices were all calibrated by applying AC voltage of known value to avoid error and improve accuracy. All the system is connecting to an oscilloscope and a computer (second control desk) for collecting, recording and analysing all the data.

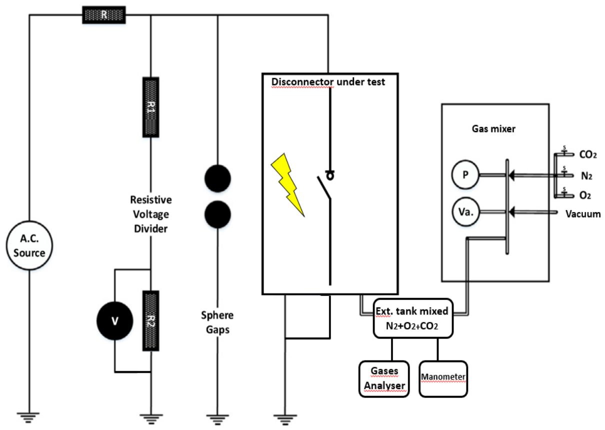
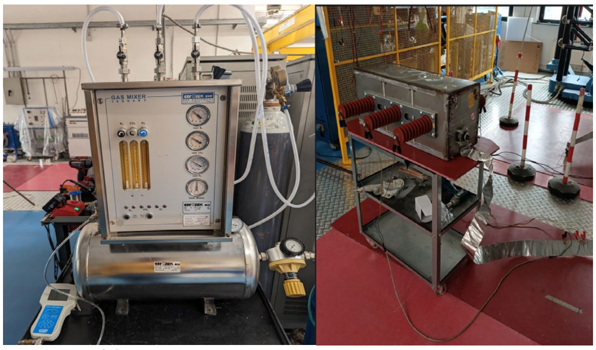


Fig. 1 Schematic diagram experiment setup

The method of experiment is an impulse withstand 3 phases AC voltage test based on standards IEC62271-102 ed.2 and [6] IEC62271-1 ed.2, test procedure B of [8] IEC 60060-1. The object under test is a 24kV rated voltage medium voltage disconnector. It has a structure based on a welded stainless steel metallic tank with inside the electric circuit made with copper busbars. Externally there is a mechanism able to manually open and close the disconnector. Test will start in closed position. Before start with the lightning impulse voltage test, the disconnector has to be filled with the gas mixture. The whole apparatus is a sealed system (according to the IEC standard). The first operation to do is to empty the full circuit and the disconnector with a vacuum pump, in order to be sure that the full volume is clean from impurity and humidity. The vacuum pump is able to de-pressure the whole circuit at around 10^{-4} kPa. After that is necessary to prepare the gas mixed ratio in an external tank where is possible to keep under control pressure and real mixed ratio. As a matter of fact, the gas mixer device at the beginning of the circuit allow to mix gases into the external tank but the real ratio has to be verified after 6 hours of filling, in order to be sure that gases remain stable. A dedicated gas analyser, directly connected to the external tank, check constantly the mixed ratio, so it is possible to adjust the mix by gas mixer. Once reached the desired ratio, the last step is to fill the disconnector at the set pressure, taking advantage of the higher pressure of external tank. So, the variables to measure are:

Mix ratio = $\%N_2$, $\%CO_2$, $\%O_2$

P_{re} = 20kPa / 100kPa / 200kPa



Photos of filling pneumatic circuit and disconnector

TEST SESSIONS

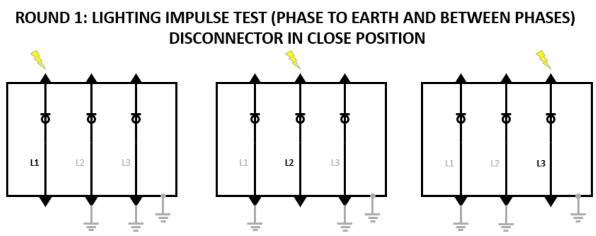
Once the tank is filled at the desired pressure, it is later connected to the three phases AC electrical test circuit, in order to perform the lighting impulse voltage test. It consists of applying to the object two sequences fixed sinusoidal wave with different values and purpose. The first sequence is for a phase to earth and between phases test, the second is across the insulating distance. Different session has been conducted for covering all the possible configuration. Here the first three round electrical parameters (ref. table 1 IEC62271-1 ed. 2.0):

U_r = 24kV

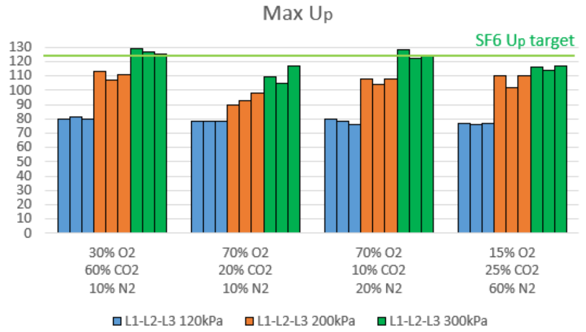
U_p = 125kV

F_r = 50Hz

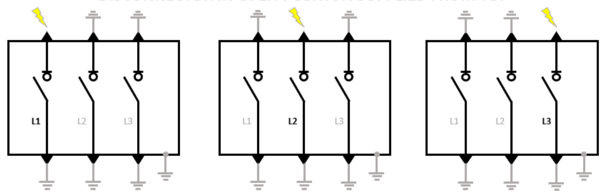
Test is successful if the number of disruptive discharges does not exceed two for each complete series. Test is performed increasing the value up to 125kV (that is the reference of SF6 performance) for finding the highest insulation limit performance of gases mix. For reducing the quantity of the test, we have decided to set in advance four different mix, based on the analysis done in a previous study [5], physical and practical consideration taking care of safety, cost and available resources. Further combination with different percentage or even single pure gas could be tested later in case we would find out relevant reasons o relationship to go into detail. Here the results:



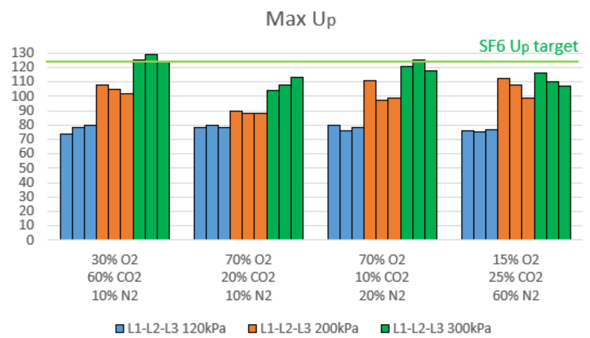
Pre	Mxr			L1 Upmax(kV)	L2 Upmax(kV)	L3 Upmax(kV)
20 kPa	10% N_2	60% CO_2	30% O_2	80	81	80
	10% N_2	20% CO_2	70% O_2	78	78	78
	20% N_2	10% CO_2	70% O_2	80	78	76
	60% N_2	25% CO_2	15% O_2	77	76	77
100 kPa	10% N_2	60% CO_2	30% O_2	113	107	111
	10% N_2	20% CO_2	70% O_2	90	93	98
	20% N_2	10% CO_2	70% O_2	108	104	108
	60% N_2	25% CO_2	15% O_2	110	102	110
200 kPa	10% N_2	60% CO_2	30% O_2	129	127	125
	10% N_2	20% CO_2	70% O_2	109	105	117
	20% N_2	10% CO_2	70% O_2	128	122	124
	60% N_2	25% CO_2	15% O_2	116	114	117



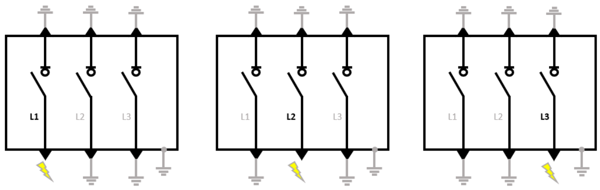
ROUND 2: LIGHTING IMPULSE TEST (PHASE TO EARTH AND BETWEEN PHASES)
DISCONNECTOR IN OPEN POSITION SUPPLIED FROM TOP



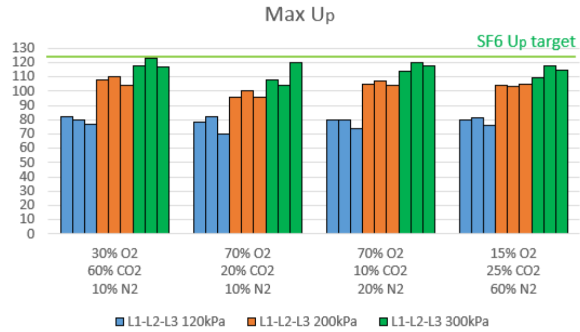
Pre	Mxr			L1 Upmax(kV)	L2 Upmax(kV)	L3 Upmax(kV)
20 kPa	10% N_2	60% CO_2	30% O_2	74	78	80
	10% N_2	20% CO_2	70% O_2	78	80	78
	20% N_2	10% CO_2	70% O_2	80	76	78
	60% N_2	25% CO_2	15% O_2	76	75	77
100 kPa	10% N_2	60% CO_2	30% O_2	108	105	102
	10% N_2	20% CO_2	70% O_2	90	88	88
	20% N_2	10% CO_2	70% O_2	111	97	99
	60% N_2	25% CO_2	15% O_2	112	108	99
200 kPa	10% N_2	60% CO_2	30% O_2	125	129	124
	10% N_2	20% CO_2	70% O_2	104	108	113
	20% N_2	10% CO_2	70% O_2	121	125	118
	60% N_2	25% CO_2	15% O_2	116	110	107



ROUND 3: LIGHTING IMPULSE TEST (PHASE TO EARTH AND BETWEEN PHASES)
DISCONNECTOR IN OPEN POSITION SUPPLIED FROM BOTTOM

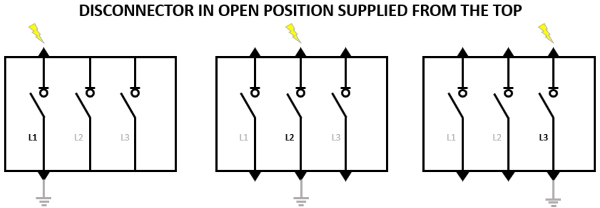


Pre	Mxr			L1 Upmax(kV)	L2 Upmax(kV)	L3 Upmax(kV)
20 kPa	10% N_2	60% CO_2	30% O_2	82	80	77
	10% N_2	20% CO_2	70% O_2	78	82	70
	20% N_2	10% CO_2	70% O_2	80	80	74
	60% N_2	25% CO_2	15% O_2	80	81	76
100 kPa	10% N_2	60% CO_2	30% O_2	108	110	104
	10% N_2	20% CO_2	70% O_2	96	100	96
	20% N_2	10% CO_2	70% O_2	105	107	104
	60% N_2	25% CO_2	15% O_2	104	103	105
200 kPa	10% N_2	60% CO_2	30% O_2	118	123	117
	10% N_2	20% CO_2	70% O_2	108	104	120
	20% N_2	10% CO_2	70% O_2	114	120	118
	60% N_2	25% CO_2	15% O_2	109	118	115

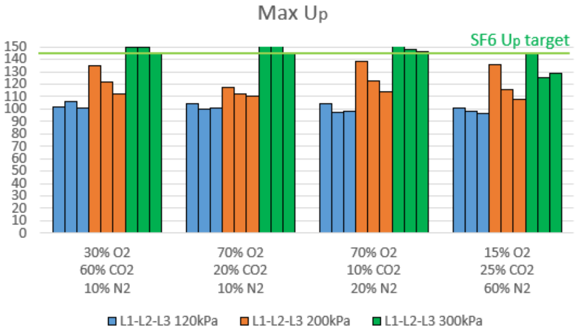


Here the second-session parameters (ref. table 1 IEC62271-1 ed. 2.0):
Ur = 24kV
Up = 145kV
Fr = 50Hz
As in the first session, test is successful if the number of disruptive discharges does not exceed two for each complete series. Test is performed increasing the value up to 145kV (that is the reference of SF6 performance) for finding the insulation limit performance of gases mix. Here the results:

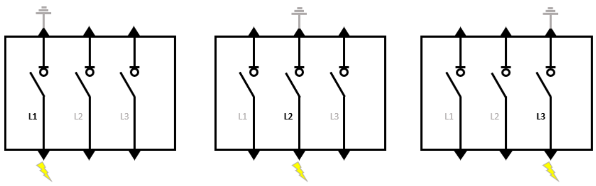
ROUND 4: LIGHTING IMPULSE TEST (ACROSS THE INSULATING DISTANCE)
DISCONNECTOR IN OPEN POSITION SUPPLIED FROM THE TOP



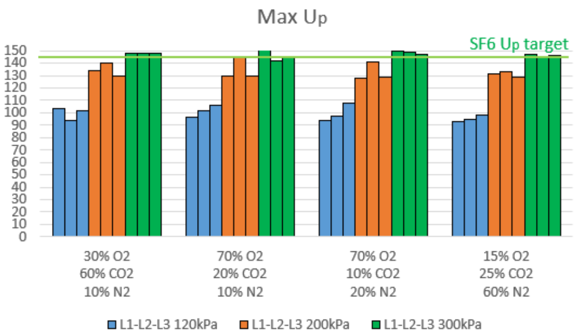
Pre	Mxr			L1 Upmax(kV)	L2 Upmax(kV)	L3 Upmax(kV)
20 kPa	10% N2	60% CO2	30% O2	102	106	101
	10% N2	20% CO2	70% O2	104	100	101
	20% N2	10% CO2	70% O2	104	97	98
	60% N2	25% CO2	15% O2	101	98	96
100 kPa	10% N2	60% CO2	30% O2	135	122	112
	10% N2	20% CO2	70% O2	117	112	110
	20% N2	10% CO2	70% O2	138	123	114
	60% N2	25% CO2	15% O2	136	116	108
200 kPa	10% N2	60% CO2	30% O2	150	150	145
	10% N2	20% CO2	70% O2	154	155	145
	20% N2	10% CO2	70% O2	151	148	146
	60% N2	25% CO2	15% O2	145	125	129



ROUND 5: LIGHTING IMPULSE TEST (ACROSS THE INSULATING DISTANCE) DISCONNECTOR IN OPEN POSITION SUPPLIED FROM BOTTOM



Pre	Mxr			L1 Upmax(kV)	L2 Upmax(kV)	L3 Upmax(kV)
20 kPa	10% N2	60% CO2	30% O2	103	94	102
	10% N2	20% CO2	70% O2	96	102	106
	20% N2	10% CO2	70% O2	94	97	108
	60% N2	25% CO2	15% O2	93	95	98
100 kPa	10% N2	60% CO2	30% O2	134	140	130
	10% N2	20% CO2	70% O2	130	145	130
	20% N2	10% CO2	70% O2	128	141	129
	60% N2	25% CO2	15% O2	131	133	129
200 kPa	10% N2	60% CO2	30% O2	148	148	148
	10% N2	20% CO2	70% O2	154	142	145
	20% N2	10% CO2	70% O2	150	149	147
	60% N2	25% CO2	15% O2	147	145	146



NOMENCLATURE

U_r = rated voltage (kV)
U_p = rated lightning impulse withstand voltage (kV)
F_r = rated frequency (Hz)
AC = Alternate Current (A)
P_{re} = Relative filling pressure (Pa)
L1 = Disconnector phase 1
L2 = Disconnector phase 2
L3 = Disconnector phase 3

CONCLUSIONS

Perform all the tests in different configurations have taken a lot of time but results are interesting. The four natural gases mixture with three different filling pressure have given important data that we can comment and summarize in these points:

- For reaching an insulation performance comparable with SF6, the key and the most important variable is the filling pressure (and consequently, the design pressure). It is evident that more pressure means more performance. Analysing data according to an assessment based on average values, we can see that we had an increase of roughly +25% of performances rising P_{re} from 20kPa to 100kPa and another +25% rising again value up to 200kPa (see fig. 2-3)

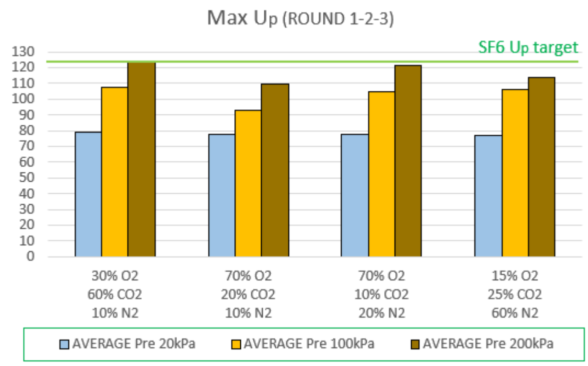


Fig. 2

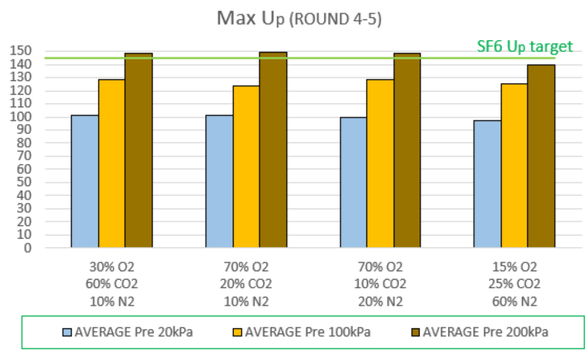


Fig. 3

- The best mix has been 30%O_2 60%CO_2 10%N_2 that highlight the importance of CO_2 and O_2 in the mixture. Further detailed analysis should be done for understanding if N2 gives a real add value into the mixture or not. Moreover, these results should be

compared with the single gas performances, just to verify that a mixture is better than a single natural gas (pure CO_2 or N_2, O_2 is excluded for risk of stoke fire)
- It is demonstrated, as guessed according to other study and literature, the importance of O_2 in the mixture, that has improved distinctly the performances with a significantly change for percentage starting from 30% in the gas mixture. However, O_2 percentage higher than 24% in a gas mixture can increase rapidly the risk of stoke fire due to is a comburent, so further investigation and risk assessment should be done for validating a possible using (that involves all the components and material inside the disconnector).

Plenty of variables are implicated in this multi-physical phenomenon, so try to made calculations and software simulations to address the design but is good but not enough: a lot of practical test has to be performed to design a reliable, safe and cost-effective solution. The path is traced because results are in any case encouraging, but there are still a lot of research, investment and arguments to take care for finding a complete alternative SF6 solution, especially for the apparatus where different electrical performance are required (arc quenching).

REFERENCES

[1] Regulation (EU) No. 517/2014 of the European Parliament and of the Council of fluorinated greenhouse gases and repealing Regulation (EC) No. 842/2006

[2] John Owens, Ang Xiao, Jason Bonk, Michael DeLorme and Agnes Zhang, “Recent development of Two Alternative Gases to SF6 for High Voltage Electrical Power Applications”, published on Energies, August 2021

[3] René Smeets, Nadew Belda, Kema Labs John Owens, “High-voltage switchgear: The road towards SF6 alternatives” published from CESI, September 2021

[4] ECHA/NR/23/04: ECHA receives PFASs restriction proposal from five national authorities

[5] IEC 62271-102 ed 2.0: Alternating current disconnector and earthing switches

[6] M.S. Dincer, S.S. Tezcan, H. Duzkaya, S. Dincer, “Synergism analysis in dielectric strength of CO2+N2+O2 ternary mixtures”, Alexandria University Engineering Journal, August 2021

[7] IEC62271-1 ed.2.0: Common specifications for alternating current switchgear and controlgear

[8] IEC 60060-1 ed. 3.0: General definitions and test requirements

VITA

Luigi Bellofatto has a Bachelor of science in electronic engineering and management, a Master of Science and the PhD in Electronic Engineering from the Politecnico of Milan. He has been working with Skema since 1997 and after a significant experience as Electrical Engineer and Lead Project Manager and he has been involved in several major international Oil & Gas projects both onshore and offshore; now he is working in Imesa SpA as CEO. He is a member of the PCIC Europe committee and holds the position as Technical Secretary.

Pietro Sigismondi graduated from National Institute Technology and Industry in Electrical Engineering in 1995. He has been a design engineer for Schneider Electric since 1999, with extensive experience in medium and low voltage power distribution. Member of Italian committee CEI CT17 and Lean Six Sigma Black Belt certificated, he is currently R&D and Mechanical Engineering Manager in Imesa company.