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Recent Development of SF_6 Alternative Switchgear Using Natural-Origin Gases in Japan

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SUMMARY

Technical evaluations of SF_6 free switchgear have been carried out based on seven requirements proposed in an application guideline by the utilities in Japan. The seven requirements for HV SF_6 free switchgear up to EHV levels include environment, health and safety (EHS), availability on normal service condition, stable supply of the gases, gas-handling, life-cycle cost (LCC), footprint comparable to existing SF_6 switchgear and future voltage coverage up to 550 kV. Under growing environmental concerns, a feasibility study to realize SF_6 free switchgear has been done based on the seven requirements for the application of natural-origin gases such as CO_2/O_2 mixtures and vacuum technology with a synthetic air insulation. This paper describes the current status and progress of SF_6 free switchgear development to cover transmission voltages.
The results show that there is no disadvantage of natural-origin gases from viewpoints of EHS, gas handling and utilization under normal service condition. In most cases, aged GISs installed in the 1970s and 1980s can be replaced with natural-origin gas switchgears based on existing design technologies due to the larger equipment size. On the other hand, it is expected in the future that more compact GIS installed later than the aged GIS will also be faced with replacement across the ages. Developments of HV switchgears using natural-origin gases have already been ongoing. Further improvements of design and technology are studied for the compactness and voltage coverage up to 550kV in the future.

KEYWORDS

SF_6 Alternatives - The Seven Requirements - Environment, Health and Safety (EHS) - Natural-Origin Gases - CO_2/O_2 Mixtures - Synthetic Air - N_2/O_2 - Vacuum Circuit Breaker (VCB)

1. INTRODUCTION

Since SF_6 had been first targeted for emission reduction by the COP3 Kyoto protocol in 1997, the electrical industry has made significant effort in the development and implementation of SF_6 applications in transmission and distribution networks. In Japan, the domestic guideline of SF_6 gas handling for electric power equipment was established in 1998, and the voluntary action plan to control and reduce SF_6 emissions based on the standards was also established in the same year[1]. The first target emission rates of less than 3% during maintenance and less than 1% during disposal of equipment were achieved by 2005. Since then, emissions have been kept low successfully and continuously.

On the other hand, research and development of SF_6 alternatives such as performance evaluations of gas mixtures using artificial fluorinated gases based on state-of-the-art current interruption technology and expanding applications of vacuum interruption to higher voltage ratings have been proceeding due to recent high interest in global environment conservation. It has been reported 170kV and 50kA was reached today as breaking capability with SF6 alternatives for HV applications. [2].

Technical evaluations of SF_6 free switchgear have been carried out based on the seven requirements proposed in an application guideline by utilities. Under growing environmental concerns, a feasibility study to realize SF_6 free switchgear was restarted based on the seven requirements for the application of natural-origin gases such as CO_2/O_2 mixtures and vacuum technology with a synthetic air insulation. This paper reports the current status and progress of SF_6 free switchgear development to cover all transmission voltages.

2. RESEARCH AND DEVELOPMENT STATUS ON THE TECHNOLOGIES REGARDING NATURAL-ORIGIN GASES AND THE COMPATIBILITY WITH THE SEVEN REQUIMENTS

The 'ideal' alternative solution should have equivalent functionality, safety, reliability, and economic potential as well as environmental superiority. Any of the proposed SF_6 alternatives so far include their inherent pros and cons for those points. It is important to consider whether the disadvantage(s) will be potentially solved by future improvements in design technology or not (in other words, whether the disadvantage(s) is determined by only the inherent properties of the gas or not). Natural-origin gas-based solutions essentially fulfil utilities' demands because there are no disadvantages which cannot be solved by design improvement, i.e. no disadvantage determined by only the inherent properties of the gas (e.g. boiling temperature, toxicity, GWP, decomposition by electric arc, and so on). On the other hand, equipment size adopting natural-origin gases are ineluctably larger than that with artificial fluorinated gas based on the same design scheme due to lower dielectric strength of the gas. These disadvantages however, will be potentially overcome with design technology improvement as well-demonstrated in the history of past SF_6 technological developments.

In Japan, the 7 requirements have been considered as guidelines for the evaluation of SF_6 alternative technology[3][4]. The technical items are listed in A) to L) below. The relevance between these items and the 7 requirements and correspondent chapters are summarized in Table I.

A) Physical properties and environmental potentials
B) Decomposed gases and solid by-products
C) Toxicity including decomposed products
D) Safety
E) Operating pressure and temperature range
F) Material compatibility
G) Gas availability
H) Gas mixture quality control
I) Erosion of arcing contacts and nozzles
J) Dielectric performance
K) Interruption performance
L) Feasibility studies for higher ratings and compactness

When screening gases from a list of 8,568 general materials, considering the fundamental requirements from the practical viewpoint of a high-voltage dielectric gas, the possible candidates that can be used as a single gas or a main gas of a mixture are eventually narrowed down to only three gases; namely N_2, CO_2 and O_2, as shown in Figure 1.[5] It can be noted here that the selected gases (N_2, CO_2 and O_2) are all natural-origin ones.

Table I The "7 requirements" to evaluate SF_6 alternative solutions [3][4], and the relevant technical items.

No.	Categories	Requirements	Relevant technical items	Outlook with natural-origin gas solutions	Refer to
1	EHS	Lower risk of toxicity of decomposition gas and by-product than SF_6.	A, B, C, D	For CO_2/O_2, arced gas includes CO or O_3, but the acute toxicity level stays in Category 6 (harmless) even after abnormal heavy fault interruptions. For synthetic air no harmful characteristics including arc decomposed condition.	2.1
2	Service Condition	Normal use conditions specified in the standard. (e.g. operation in -25 °C)	E	Service condition even in cold regions below -40°C is not a concern based on low liquefaction temperature for wide pressure range in case of natural-origin gases (N_2, CO_2 and O_2).	-
3	Stable Supply	Stable supply of the gas, preferably by multiple suppliers.	G	Natural origin gasses such as CO_2/O_2 and Synthetic air are quite commonly supplied by a lot of general industrial gas manufacturers.	-
4	Gas Handling	Simple gas handling.	H	Evaluated that the impact of dispersion in mixture composition on dielectric performance is limited to the range of +/-1%, which is well manageable by a design role and verified by a type test.	2.2
5	Life Cycle Cost	Reasonable life cycle cost, including equipment, installation, maintenance, etc.	F, I, J, K	Expected life time and operation cost with natural-origin gas equipment can be equivalent compared to the existing SF6 equipment, while design improvements and technological innovations to minimize initial cost should be necessary.	2.3
6	Footprint	Possible to replace in restricted locations, such as outdoor and underground substations.	J, K	Possible to replace currently aged GIS manufactured in the 1970s and 1980s with natural-origin gas equipment.	2.4
7	Voltage Coverage	Feasibly scalable up to the extra high voltage (EHV) rating 550 kV.	K, L	New design approaches and specification rationalizations will be studied and positively adopted to minimize equipment size. Both 72/84kV kV 31.5 kA GIS and 168 kV 40 kA VCB using natural-origin gases will be piloted soon by 2023 in Japan. The authors, as Japanese manufacturers and utilities, will aim 550 kV by the end of 2029.	2.5

CO_2 is one of the representative global warming gases, but it should be noted that this is rather a CCU (Carbon Capture and Utilization) application and does never generate brand-new CO_2 on the earth.

Criteria of selection	Remaining quantity
Total number of surveyed material (from Chemical Handbook)	8,568
Being Gas state at room temperature (Boiling temperature under 25 deg C.)	189
Not contain chlorine element (Cl)	163
Not contain bromine element (Br)	149
Having no toxicity and explosibility	69
Not having high reactivity	50
Omitting gases of unknown properties	20
GWP <=1	9
Dielectric strength > 10% of SF6	3 (N2, CO2, O2)

Figure 1 Screening of practical alternative gas that can be used as a single gas or a main gas of a mixture for high-voltage equipment application. [5]

2.1. Environment, Health and Safety (EHS)

A) Physical properties and environmental potentials

Table II shows the general properties of gas mixtures for SF_6-alternatives. SF_6 is given as the reference in this Table[6][7][8]. Insulation strength of artificial gases such as C_5-FK and C_4-FN mixtures is higher than that of natural origin gases. Also, their GWPs are lower than that of SF_6. Accordingly, high-voltage circuit breakers using these artificial mixture gases have been developed in Europe and Korea.

The general properties of natural origin gases (CO_2, CO_2/O_2, N_2/O_2 (synthetic air)) are also shown in Table II. They can be released to atmosphere, because their GWPs do not exceed 1 and their toxicity level evaluated by LC50 and TWA are negligibly low as they are commonly used in lots of industries and products. Additional heaters which prevent their liquefaction are also not necessary in less than -50 °C circumstance, even if their pressure will be increased for insulation and switching performance improvement.

Table II General properties of gas mixtures for SF_6-alternative [6][7][8]

Gas	Pressure [MPa-g]	Min, operating temperature [°C]	GWP [100 year]	ODP	Toxicity	
					LC50 [ppmv]	TWA[ppm] (200days x 8h average exposure limit)
(SF_6)	0.43 to 0.6	-41 to -31	25,200(*1)	0	-	1000
CO_2	0.6 to 1.0	<-48	1	0	>4.7.e5	5000(*2)
CO_2/O_2(30)	0.7	<-56	0.7	0	>6.7.e5	5000(*2)
N_2/O_2 (Synthetic air)	0.15 to 1.0	<-180	0	0	0	∞
$CO_2/C_5FK/O_2$	0.7	-5 to +5	1	0	>2.e5	225(*3)
CO_2/C_4FN	0.67 to 0.82	-25	327 to 690	0	>1.e5	65(*4)

ODP: Ozone Depletion Potential, GWP: Global Warming Potential, TWA: Time Weighted Average
(*1) Value referred from AR6 (IPCC Sixth Assessment Report), (*2) Value for CO_2[7], (*3) Value for C_5-FK[8], (*4) Value for C_4-FN[8]

B) Decomposed gases and solid by-products

C) Toxicity including decomposed products

i) CO_2/O_2: Decomposed gases and solid by-products generated by discharge, especially high power arcing. Table III shows amount of the decomposed gas components detected in a 490 litter enclosure after being exposed to 1,500 kJ of arc energy (corresponding to a typical enclosure volume of an 145 kV 40 kA SF_6 dead tank breaker, and arc energy of approx. 10 times of T100s interruptions) for both a pure CO_2 gas case and a CO_2/O_2 (30%) gas mixture cases. The table also includes the acute toxicity criteria LC50(4 hours) of each component. The relevant decomposed gases are CO, HF and O_3 (slight H and F come from humidity and PTFE nozzle ablation, respectively). In other words, it is these three decomposed gases that should be noted in a CO_2/O_2 gas mixture application, even though abnormally massive arc energy was injected into the enclosure in a short period in this case, compared to actual operations. It is readily seen in Table III that 30% O_2 drastically reduces CO generation. HF and O_3 are also concerns but should be managed with suitable absorbent as has been well proven with traditional SF_6 switchgears. Figure 2 shows how well a suitably selected absorbent works for all the three concerned gases.

Table III. Decomposed gases detected after arcing in pure CO_2 and CO_2/O_2 mixture.
(490 litter enclosure after 1,500kJ of arc energy)
(Unit: ppmV)

	Toxicity LC50	Pure CO_2	CO_2/O_2(30%)
CO_2	141,618 /4h	(Balance)	(Balance)
O_2	-	196	299,880
CO	2,612 /4h	7,000	120
HF	642 /4h	100	250
O_3	11 /4h	35	25
H_2	> 15,000/1h	15	4
CH_4	> 500,000/2h	2	2

Figure 3 shows the acute toxicity assessment of the arced gases as a function of accumulated fault duty. As new gas, SF_6, CO_2 and CO_2/O_2(30%) are all considered Category 6 (relatively harmless) on the Hodge-Sterner acute toxicity scale [9]. Figure 3 clearly shows the positive effect of O_2 addition to CO_2. The acute toxicity level of CO_2/O_2 starts lower and uniquely stays in Category 6 even after 1,500 kJ of multiple heavy fault interruptions.

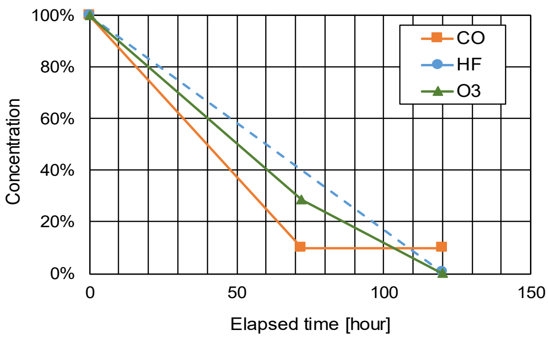


Figure 2. Reduction of decomposed gas concentrations CO_2/O_2 gas mixture with a specific absorbent

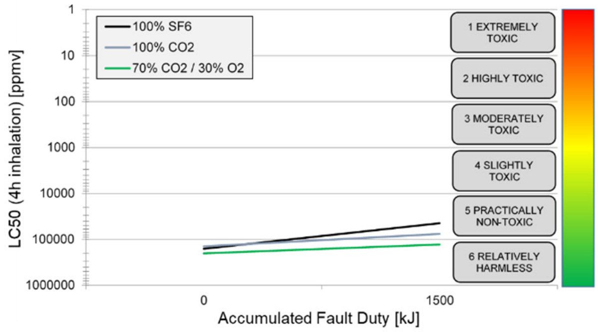


Figure 3. Acute toxicity assessment: Accumulated fault duty vs. LC50(4h) on Hodge-Sterner scale, up to 1,500 kJ in 490 liter enclosure.

ii) Synthetic air: It is reported that no harmful chemical reactions and no harmful by-products are expected for typical insulation or small current interruption applications, considering natural-origin gases such as N_2, CO_2 and synthetic air, in the article of the recyclability in the technical brochure of CIGRE WG D1.51 (TB730)[10] [11] [12].

D) Safety (flammability, etc.)

It's self-evident for synthetic air to be non-flammable and the safety of CO2/O2 has been also confirmed. Extensive fault testing has been performed with CO_2/O_2(30%) gas mixtures. Despite the presence of 30% O_2 and a strong ignition source (high current arc) no residual burning or explosion has ever occurred.[13] In this manner, it has been experimentally demonstrated that materials commonly used for switchgear applications, like fluorine resins (PTFE nozzle) and metals of Al, Fe, Cu, W and so forth, show no problem in CO_2/O_2(30%) gas mixtures, in which proper attention should be paid not to use an irregular organic material close to a hot interrupting part. During the development process, all manner of breakdowns occur while searching for the design limits; namely faults across the arcing and main contacts, ground faults, and faults across solid insulation, etc. including abnormally long arcing times. Under no circumstances have these breakdowns led to an uncontrolled or sustained continuation of the arc.

Figure 4 is the experimental assessment result of the flammable range of a combustion gas CH4 in CO_2/O_2. [14] It demonstrates the fact that CH_4 concentration lower than 5% never cause combustion even for any O_2 concentration, and also O_2 concentration lower than 20% never cause combustion even for any CH_4 concentration, which could support the experience in a number of CO_2/O_2 breaker testing.

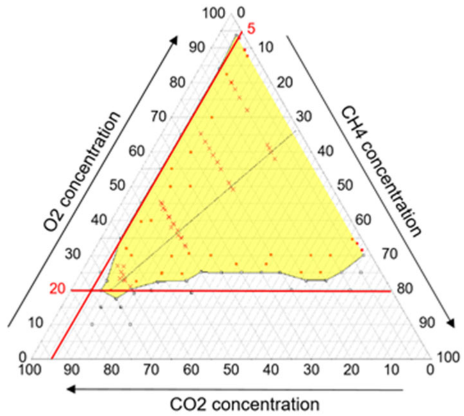


Figure 4. Experimental assessment result of flammable range of a combustion gas CH4 in CO_2/O_2 (yellow area indicates the flammable range). [14]

2.2 Gas Handling

H) Gas mixture quality control

As discussed in 2.1 B) C), changes in CO_2 and O_2 concentration have been proved to be very limited. Almost no changes occur as seen in Table III, even after multiple heavy fault interruptions. However, certain range of dispersion in mixture composition exist due to gas handling processes and potential uncertainness of measurement instruments. It is of importance from the practical point of view to assess this uncertainness's impact on the dielectric performance of the gas mixture and to take into account in the hardware design. Here, supposing +/-3% change in O_2 concentration in CO_2/O_2(30%) gas mixture as a rather conservative number considering a commercially available, handy, and cheap O_2 sensor, its impact on dielectric performance is evaluated. As shown in Figure 5, even with this conservative condition, the impact is limited to the range of +/-1%, which is well manageable by a design role and verified by a type test. Furthermore, this fact may be quite beneficial for asset management because it suggests the possibility that, similar to SF_6 equipment, only filling pressure monitoring should be normally sufficient (no need to measure all concentration of mixture components) for CO_2/O_2 gas mixture equipment.

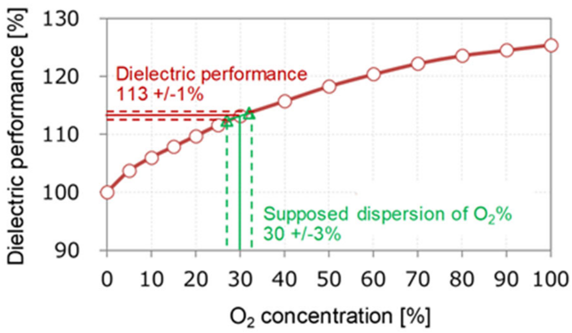


Figure 5. Impact of O_2 % dispersion on dielectric performance of CO_2/O_2 gas mixture equipment. (Supposing dispersion of 30 +/-3%)

2.3 Life Cycle Cost (LCC)

F) Material compatibility

The long-term compatibility of internal parts with O_2 is considered a part of the technology development. These include not only general metal oxidation, but also lubricants, coatings, surface treatments, adsorbents, contacts and seals.[8] Figure 6 shows some examples of how to validate entire systems of lubricants and coatings in long term aging tests. The general approach is to use SF_6 as the baseline for comparison and subject test coupons to thousands of hours at elevated temperature. As the tests progress, colour, viscosity and adhesion are monitored in both the test gas and SF_6. No significant issue has been confirmed for CO_2/O_2. Contact systems of base metal, plating and lubricant are validated in a similar manner except that in addition to the above criteria, contact resistance is also monitored and recorded approx. every 1,000 hours. By selecting suitable plating material for the CO_2/O_2 gas mixture, it is confirmed that contact resistance has been keeping practically stable in the ongoing test.

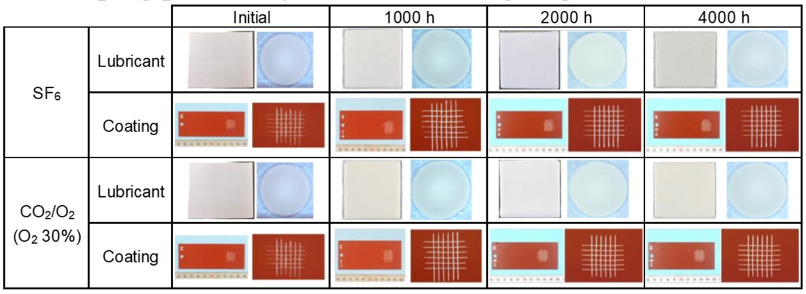


Figure 6. Examples of long-term material compatibility test (lubricants and coatings in CO_2/O_2(30%)).

I) Erosion of arcing contacts and nozzles

<u>i) CO_2/O_2:</u> Particularly for a gas circuit breaker, erosion rates of PTFE nozzle and W/Cu arcing contact materials are important factors to determine how durable the nozzle and contacts are over repetitive current interruption stresses. Figure 7 shows the comparison of erosion rates among different O_2 concentrations, which were experimentally obtained after 12 heavy current interruptions in the range of 23 to 29 kA with a pressure of 0.8 MPa-abs. The erosion rate of the plug contact was almost equivalent, while the nozzle and the tulip contact were both lower with higher O_2 concentration. Physical interpretations of these experimental outcomes require very complicated analysis due to the dynamic and transient nature of the phenomena, but it can be concluded that the additional O_2 up to at least 30% did not cause any significant negative effect on erosion of PTFE nozzle and W/Cu arcing contact materials.

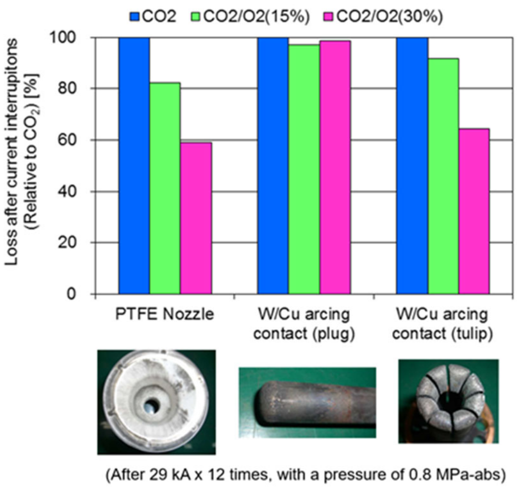


Figure 7 Comparison of erosion rates of PTFE nozzle and W/Cu arcing contact materials among different O_2 concentrations.

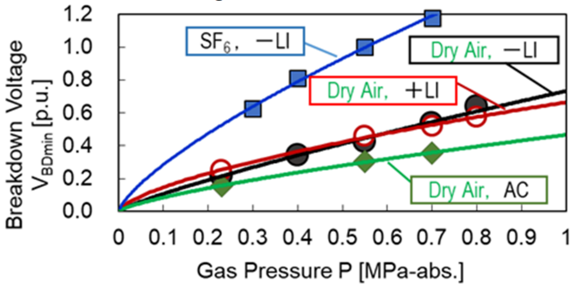
<u>ii) Synthetic air:</u> There is no influence of short circuit current interruption in the space of the synthetic air in the enclosure since the it is done by vacuum interrupter (VI) in case of synthetic air insulated vacuum circuit breakers (VCB). For example, 10,000 load current interruptions can occur without the replacement of its VI unit. Unlike the case of the VCB, where the consumable parts such as puffer nozzle and arcing contacts have to be replaced every 5,000 times of them in case of GCB.

2.4 Footprint

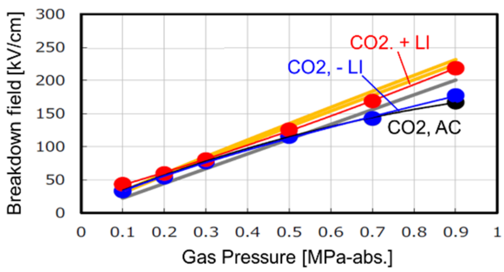
J) Dielectric performance

The investigation of the dielectric performance in the gas is necessary to decide the design gas pressure, the equipment size, and to secure the long-term reliability. For the dielectric design of equipment that utilizes natural-origin gas, much research has been carried out to clarify the various characteristics such as the area effect, the gas pressure dependence, the polarity effect, the effect of particle contamination, etc.

Figure 8 shows the pressure dependence of minimum breakdown voltage under a quasi-uniform electric field in dry air (synthetic air) and CO_2. [15][16] The minimum breakdown voltage of LI and AC increased with the rise of gas pressure. In the case of 0.55 MPa in dry air, the dielectric strength of the LI voltage was about 60% lower than that in SF_6 gas. However, with the pressure increase from 0.55 MPa to 0.8 MPa, the minimum breakdown voltage of dry air rose about 20% higher.



(a) Synthetic air



(b) CO_2

* V_{BDmin} is the breakdown voltage value V0.1% under the condition of wide effective area.

* The values were normalized based on the negative polarity of SF6 gas under the 0.55 MPa condition.

Figure 8. Pressure dependence of minimum breakdown voltage.

Replacement of aged substation equipment is expected to increase in the future. Considering the expected increase in the size of equipment insulated by natural-origin gas, it is necessary that the equipment can be replaced in places where the installation space is limited, such as indoor substations. Figure 9 shows comparisons of estimated equipment dimensions between SF_6 and natural-origin gas for HV class (three-phase enclosed) and EHV class (isolated phase) respectively. Equipment dimensions with natural-origin gases, which have lower dielectric performance than SF_6, increase in all cases compared to the latest type of GIS using SF_6, as far as those designs are based on conventional technologies. On the other hand, currently aged GISs that need to be considered for replacement were mainly manufactured in the 1970s and 1980s. Those bus sizes are 1.2 to 1.6 times larger than the latest type of GIS. In most cases, those larger bus sizes are equal to or exceed the size of natural-origin gas equipment. Therefore, the footprint of natural-origin gas equipment is basically equal to or smaller than the aged GIS. This leads to possible replacement of currently aged GIS to natural-origin gas equipment. However, it is expected in the future that more compact GIS installed later than the aged GIS will also be faced with replacement across the ages. Hence, it is important to continue research and development for further improvement of dielectric performance of natural-origin gases to get closer to the size of the latest GIS.

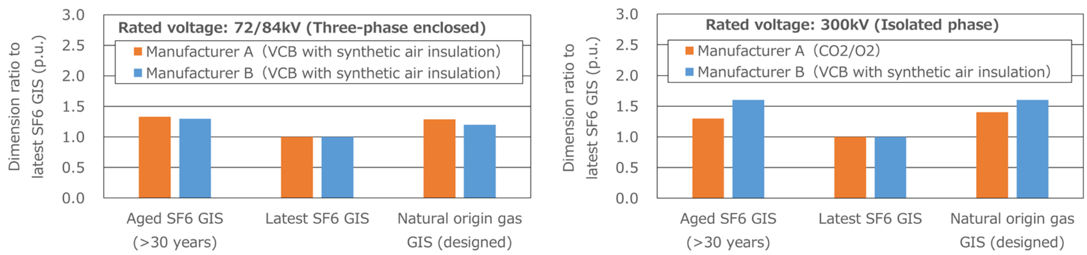


Figure 9 Estimated equipment dimensions using natural-origin gases compared with aged and the latest type of GIS

2.5 Voltage Coverage

2.5.1 Current development status[4]

Transmission and distribution equipment using SF_6 technology is currently applied mainly in the systems from 72 kV to 550 kV. The equipment using natural origin gas technology is desirable to be applied up to the highest voltage rating 550 kV in the future, since the possession rate of SF_6 gas of 204 kV rating (Nominal voltage: 187kV) and above accounts for more than 60% of the whole[17].

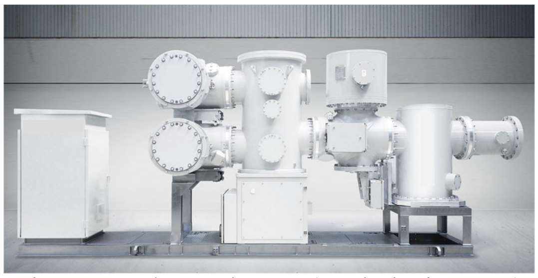


Figure 10. 72 kV 31.5kA GIS (Synthetic air + VCB)

72/84 kV 31.5 kA SF_6 free GIS consisted of a VCB with synthetic air insulation system shown in Figure 10 has completed the type test and will be installed by 2022 as the first pilot in Japan[18][19].

Also, 72.5 kV 31.5 kA and 145 kV 40 kA (Figure 11) synthetic air insulated VCBs have been under development and the former (72.5 kV 31.5 kA VCB) is planned to be on the market in 2021[20]. The development of 72/84kV kV 31.5 kA and 168 kV 40 kA VCB are also ongoing for application in Japan as well, and the latter (168 kV 40 kA VCB) will be operated in field in 2023. Furthermore, joint development of a dead-tank type 245 kV VCB will be started toward the future development of the rating up to 550 kV level[21].

Figure 11. 145 kV 40kA VCB
(Synthetic air insulated)

2.5.2 Challenges for higher ratings

K) Interruption performance

Vacuum interrupting technology is an excellent SF_6-free solution, which has been well proven with lots of commercialized products. It is known that vacuum interrupters have quite high thermal interruption capability, and extensive development works are being done to expand these applications toward higher voltage levels even up to 245 kV or more. Another option could be a gas interrupter using natural-origin gases. Figure 12 shows the experimental comparison of thermal interruption capability of CO_2-based several natural-origin gas mixtures with a full-scale breaker model. It is known that thermal interruption capability of pure CO_2 is approx. 60% of that of SF_6 [6], and Figure 12 indicates that some natural-origin gas mixtures show better performance than pure CO_2, in which CO_2/O_2 could be the most promising in terms of the interruption performance. On the other hand, the important milestone for scalability up to 550 kV should be 63 kA interruption capability, because voltage is scalable in principle from gas insulation nature, whereas interruption is not always so. At present 40 kA interruption has been achieved [8], which is, however, not a solid evidence for 63 kA possibility.

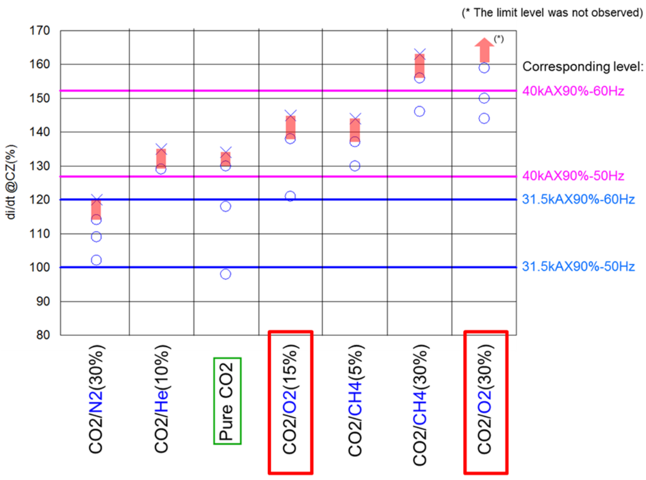


Figure 12. Experimental comparison of thermal interruption capability of natural-origin gas mixtures. [5]

L) Feasibility studies for higher ratings and compactness

It is considered that SF_6 free equipment size should be larger than that of SF_6 equipment without new breakthrough technologies to compensate the inherent performance gap between the gases. Multi-break interrupters and higher gas pressure are considered as an effective means for higher ratings. On the other hand, new design approaches are necessary to minimize the increase of the size of natural-origin gas equipment.

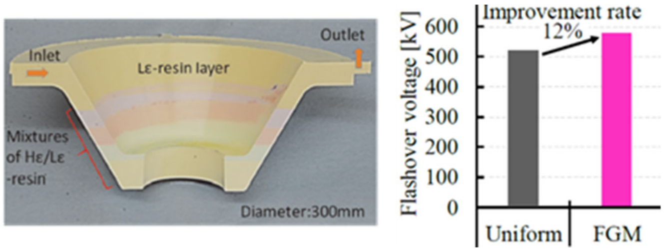


Figure 13. Dielectric performance improvement of the insulating spacer with novel ε functionally graded materials (ε-FGM) as a compactification technology of SF6 free equipment.[22]

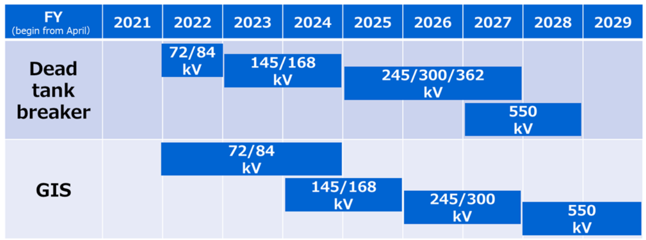


Figure 14. The roadmap of natural origin gas-insulated switchgear releases above 72 kV (as of April 2022)

Optimal equipment design with advanced analysis technologies and state-of-the-art novel technologies, such as digitization of CT/VT, innovative functional insulating materials based on nanocomposites and functionally gradient material (FGM, see Figure 13), and rationalization of circuit-breaker/switchgear specifications (e.g. rapture disc applying, withstand voltage specification) will be studied and positively adopted.

Lastly, the roadmap of natural-origin gas insulated switchgear releases above 72 kV is presented as Figure 14 by the authors. Although coverage up to 550 kV must be a great technical challenge, the authors, as Japanese manufacturers and utilities, will aim to complete it by the end of 2029 for the future sustainable T&D systems.

3. CONCLUSION

The current status and progress of SF_6 free switchgear development to cover all transmission voltages in Japan was reported. Technical evaluations of SF_6 free switchgear have been carried out based on seven requirements proposed in an application guideline by the utilities in Japan.

- There are no disadvantages of natural-origin gases from the viewpoints of EHS, gas handling and utilization under normal service condition.
- In most cases, aged GISs installed in the 1970s and 1980s can be replaced with natural-origin gas switchgears based on existing design technologies due to the larger equipment size. On the other hand, it is expected in the future that more compact GIS installed later than the aged GIS will also be faced with replacement across the ages.
- Developments of HV switchgears using natural-origin gases have already been ongoing in Japan. Further improvements of design and technology will be studied for the compactness and voltage coverage up to 550 kV in the future.

Natural-origin gas-based solutions essentially fulfil utilities' demands because there is no disadvantage which cannot be solved by design improvement. On the other hand, equipment size adopting natural-origin gases is ineluctably larger than that with artificial fluorinated gas based on the same design scheme due to a lower dielectric strength of the gas, which will be potentially overcome with design technology improvement as well-demonstrated in the history of past SF_6 technological developments.

BIBLIOGRAPHY

[1] K. Taketa et al., "Domestic situation and response based on trends in international SF_6 gas alternative technology" (IEE Japan Annual Meeting, S5-4, March 2021)

[2] T&D Europe, "Technical report on alternative to SF6 gas in medium voltage & high voltage electrical equipment" (5th March 2020)

[3] K. Nakamura: "Position on application of substation equipment using SF_6 alternative technologies in Japan" (No. B3-NGN 01, Cigre e-Session 2020)

[4] K. Nakamura, S. Tsukao, T. Nishioka, K. Taketa, T. Uchii, H. Hama,"Management of SF6 Gas Leakage from Substation Equipment and Technical Guidelines on Application of Substation Equipment using SF6 Alternative Gases in Japan" (CIGRE 2022 Session, 10736 (to be published in Aug. 2022))

[5] T. Uchii et al., "Present Status and Future Prospects of SF6 Alternative Technologies for a High-Voltage Switchgear" (Cigre SC A3 and B3 Joint Colloquium (Nagoya), No. 222, 2015)

[6] M. Seegar et al., "Recent development and interrupting performance with SF_6 alternative gases" (Electra No.291, pp.26-29, April 2017)

[7] IEC TC 17 "IEC 62271-4 ED2 HIGH-VOLTAGE SWITCHGEAR AND CONTROLGEAR" (Annex D Clause D.2.2 Protection of personnel, 2021)

[8] CIGRE WG B3.45 "Application of non-SF_6 gases or gas-mixtures in medium and high voltage gas insulated switchgear" (CIGRE Technical Brochure, TB802, 2020)

[9] H.C. Hodge and J.H. Sterner, "Tabulation of Toxicity Classes" (American Industrial Hygiene Association Quarterly, Vol. 10, No. 4, pp. 93-96, 1949)

[10] CIGRE WG D1.51 "Dry Air, N_2, CO_2 and N_2/SF_6 Mixtures for Gas-Insulated Systems" (CIGRE Technical Brochure, TB730, 2018)

[11] B. Lutz, K. Juhre, M. Kuschel, P. Glaubitz "Behavior of gaseous dielectrics with low global warming potential considering partial discharges and electric arcing" (CIGRE 2017 Winnipeg colloquium, D1 140, 2017)

[12] T. Psotta, V. Hinrichsen, B. Lutz "Breaking Capacity of Disconnectors and Earthing Switches Operated in Alternative Gases" (2018 IEEE International Conference on High Voltage Engineering and Application (ICHVE), 2018)

[13] T. Uchii et al., "Gas Handling and Lifetime Aspect of F-gas Free Switchgears Applying CO_2/O_2 Natural-origin Gas Mixture" (CIGRE 2020 AORC Web-library event, No.C000158, 2020)

[14] A Janes et al., "Experimental study of $CH_4/O_2/CO_2$ mixtures flammability" (Global Congress on Process Safety (GCPS), HAL ID. ineris-00976228, 2011)

[15] M. Miyashita, M. Sato, S. Nakauchi, Y. Yoshitomo, "Insulation Characteristics of Quasi-uniform Electric Field and Effect of Metallic Particle Contamination in Highly Compressed Dry Air" (International Symposium on High Voltage Engineering, No. 1018, 2021)

[16] T. Yasuoka et al., "Effect of Electrode Surface Roughness in High Pressure CO_2 (-0.9 MPa) under Quasi-Uniform Electric Field" (IEEJ Trans. PE, Vol. 132, No.2, pp. 139-143, 2012)

[17] S. Tsukao "Trends and requirements for SF_6 alternative technology" (Denki-Hyoron 9, 2020)

[18] Toshiba Energy Systems & Solutions Corporation and Meidensha Corporation, "Toshiba and Meidensha to develop GIS jointly using natural origin gases – aim to commercialize GIS by March 2023, contributing to carbon neutral goals –" (https://www.toshiba-energy.com/en/info/info2021_0621.htm, press released on June 21, 2021)

[19] 72kV Vacuum circuit breaker, Mitsubishi Electric Power Products, Inc.,https://0aab1c21-cdn.agilitycms.cloud/AttachmentLists/File/SA0030109001_72V%20VCB%20Solutions%20Sales%20Aid.pdf (Accessed on 30th September, 2021)

[20] Siemens Energy and Mitsubishi Electric sign MoU to move faster to develop gas solutions with zero global-warming potential in the high-voltage power transmission industry", Mitsubishi Electric Power Products, Inc., (https://www.mitsubishielectric.com/news/2021/pdf/0608.pdf Accessed on 30th September, 2021)

[21] S. Tsukao et al., "Actual use survey and maintenance practice of circuit breakers for frequent switching applications" (Cigre e-Session 2020, A3-206, 2020)

[22] M. Hikita, "Innovative Functional Insulating Materials Development for Advanced Electric Power Apparatuses" (IEEJ/IEEE International Symposium on Electrical Insulating Materials (ISEIM), No. SP2-1, 2020)