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Development of SF_6-Free 72/84kV GIS Using Synthetic Air as an Alternative to SF_6

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SUMMARY

Although emissions of SF_6 gas used in existing gas-insulated switchgears (GIS) in Japan have been successfully controlled by strict industry-level management and recycling of SF_6 gas, an alternative solution to SF_6 technology is highly expected from a long-term perspective toward the carbon neutrality goal. With this background, the 72/84 kV GIS for power grids was newly developed, and successfully tested, installed, and energized in February 2023 as the first Japanese pilot substation with a modern SF_6 alternative solution. In the present GIS design, a compact three-phase encapsulated layout with a vertical circuit breaker and frontal bus bar arrangement was adopted, which enables easy expansion and replacement for existing substations. The VCB for this GIS was designed based on well-proven vacuum interrupter technologies. Fundamental materials (e.g., seals, greases, insulators, etc.) used in the GIS have been verified in long-term aging tests, and, as a result, are mostly identical to those used for conventional SF_6 GIS. Also, this GIS is designed to be applicable for digital substations based on IEC 61850.

KEYWORDS

Gas-insulated switchgear (GIS), Global warming, SF_6 emission, SF_6 alternative gas, Synthetic air, Vacuum interrupter, Natural-origin gas

1 Introduction

Many older T&D facilities that were installed during the high-growth period in Japan now need to be replaced. There is also worldwide demand to make T&D infrastructure greener together with more sustainable and renewable electricity generation. Though emissions of SF_6 gas used in existing gas-insulated switchgear (GIS) in Japan have been well controlled by strict industry-level management and recycling of SF_6 gas, an alternative solution to SF_6 technology is highly expected to support longer-term carbon neutrality goals. With this background, the 72/84 kV GIS for power grids was newly developed, and successfully tested, installed and energized in February 2023 as the first Japanese pilot substation with a modern SF_6 alternative solution.

The development was a collaboration of two manufacturers. One oversaw development of the entire GIS system and all GIS equipment adopting synthetic air as the alternative gas to SF_6 (other than the interrupter). The other oversaw the development of the synthetic air-insulated vacuum circuit breaker (VCB). In the GIS design, a compact three-phase encapsulated layout with a vertical circuit breaker and frontal bus bar arrangement was adopted, which enables easy expansion and replacement for existing substations. The VCB for this GIS was designed based on well-proven vacuum interrupter technologies. Fundamental materials (e.g., seals, greases, insulators, etc.) used in the GIS have been verified in long-term aging tests, and, as a result, are mostly identical to those used for conventional SF_6 GIS. Also, this GIS is designed to be applicable for digital substations based on IEC 61850.

In the present paper, the specifications, main features, technologies and test result are introduced.

2 Ratings

Table 1 shows the main ratings of the present 72/84 kV GIS. Each unit was developed in accordance with the latest Japanese GIS standards; namely JEC-2350:2016 [1], JEC-2300:2020 [2], and JEC-2310:2014 [3].

Table 1: Development specifications of SF_6-Free 72/84kV GIS

Rated voltage (kV)		72/84
Rated continuous current (A)		Up to 3 000
Rated short-time withstand currrent		31.5 kA - 2sec
Lightning impulse withstand voltage (kV)		350
Maximum values of temperature rise (K)	Contacts and connections	75
	Surfaces not to be touched in nomal operation	50
Duty of bus-transfer current switching for DS	Recovery voltage (V)	100
	Bus-transfer current (A)	2 400
Duty of induced current switching for ES	Recovery voltage (V)	1 500
	Induced current (A)	200
Rated frequency (Hz)		50 / 60
Insulating media	Gas	Synthetic air
	Rated gas pressure (MPa-g)	0.5
	O_2 content	21% ±1%
	H_2O Dewpoint	< -50℃

3 Technical Features

The basic configuration of the developed 72/84kV GIS is shown in Figure 1 as a typical layout example that has a cable head connecting to the underground power cable with a double bus bar system and transmission line circuit. A compact three-phase encapsulated layout with a vertical circuit breaker and frontal bus bar arrangement was adopted to match typical Japanese operations at outdoor, which enables easy expansion and replacement for existing substations. The VCB for this GIS was newly designed based on well-proven vacuum interrupter technologies.

The features of this GIS will be described in this chapter.

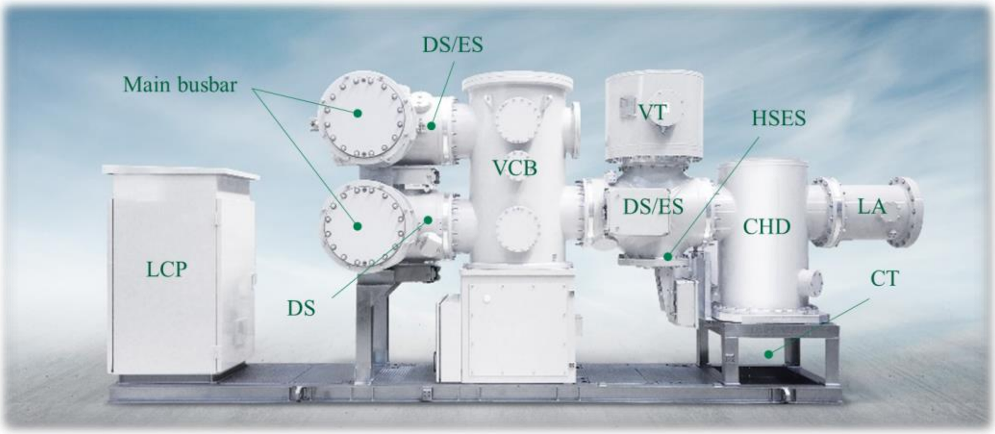

Figure 1: Basic configuration of the developed SF_6-Free 72/84kV GIS for outdoor

3.1 Selection of the SF_6-Alternative gas

Since the 2000s, much research on SF_6-alternatives for environmental purposes has been performed and a variety of solutions have been proposed. In recent years, the number of solutions has been narrowed down to two candidates: mixtures of artificial fluorinated gases and mixtures of natural origin gases such as N_2, CO_2, and O_2.

The present 72/84 kV GIS was designed to fully comply with the “Seven Requirements” [4-6] shown in Table 2 as a guideline to evaluate emerging SF_6 alternative technologies. These requirements were established by the “SF_6 Alternative Gas Study Group” composed of the following Japanese members: 11 utilities, 7 switchgear manufacturers, 6 academia and CRIEPI, together with TDGC (The Japan T&D Grid Council) and JEMA (The Japan Electrical Manufacturers’ Association) as observers. The natural-origin gas solution, namely, synthetic air-insulated vacuum circuit breaker technology, was adopted for this GIS mainly considering EHS (environment, health, and safety), future regulations, gas supply risks, and easy gas handling [7].

Although there are challenges with natural origin gas insulated system in terms of equipment size and scalability at present, these are potentially overcome by design improvements. Synthetic air is significantly inferior to SF_6 gas in terms of both insulation and current interrupting performance. Specifically, the current interruption and dielectric performance of synthetic air are approx. 10 % and 30% respectively compared to SF_6 gas at identical gas pressure. Therefore, to satisfy “replaceable footprint” in the “Seven Requirements”, various novel technologies and designs were adopted, as described in the next section.

Table 2: Suitabilities according to the guideline “Seven Requirements” for SF_6 alternative technology

Categories	Requirements
Environment Health Safety (EHS)	✓ No EHS concerns with synthetic air insulation. ✓ No decomposed gases due to short circuit interruptions.
Use condition	✓ Applicatable to outdoor use below -25℃ without a heater.
Stable gas supply	✓ Common gases used in many industries. ✓ Stable gas supply proven.
Gas handling	✓ Pre-mixed gas supply. ✓ No special handling gear needed.
Total cost	✓ Reasonable total cost expected, considering operational cost and initial cost.
Replaceable footprint	✓ Replaceable equipment size expected even for resticted cases e.g. underground substations.
Scalability	✓ Scalable to higher ratings in principle based on the natural origin gas concept.

3.2 Vacuum Circuit Breaker

The circuit breaker shown in Figure 2 was newly developed for the present GIS based on well-proven technologies used in many VCBs applied within grounded enclosures and insulated with synthetic air. Vacuum interrupters (VIs) are sealed-for-life devices that require no maintenance of the main circuit since no decomposed gas is generated when current is interrupted.

To improve reliability against multiple open/close operations, a structure with two pressure chambers, a high-pressure chamber (tank) rated at 0.5 MPa-g and a low-pressure chamber (mechanism) rated at 0.16 MPa-g, was adopted to reduce mechanical stress on the VI bellows and to reduce operating energy. High insulation performance and stabilization were achieved by applying an insulation coating on high electric field surfaces. Compared with the existing SF_6 GIS, the developed GIS meets the required performance without a significant increase in size.

The heat dissipation process of a VI is mainly by thermal conduction and radiation. Vacuum interrupters contact cooling by direct convection does not apply. In addition, synthetic air has reduced convective thermal transport capability compared to SF_6 at the same pressure. If left unaddressed, this could cause increased temperature rise. Therefore, a coating with improved radiation emissivity is applied to the conductors to enhance thermal radiation. Furthermore, by optimizing the shape and arrangement of the conductors, a current-carrying capacity of 3 000 A was achieved in a sealed synthetic air configuration [8].

The latest JEC-2300:2020 standard requires a transformer limited fault (TLF) current breaking test, which is one of the most challenging duties for a circuit breaker due to the fast RRRV and peak voltage stress. The developed VCB successfully fulfilled the 84 kV TLF requirement for 12.5 kA, and a transient recovery voltage (TRV) with 157 kV (peak) and 6.5 kV/μs.

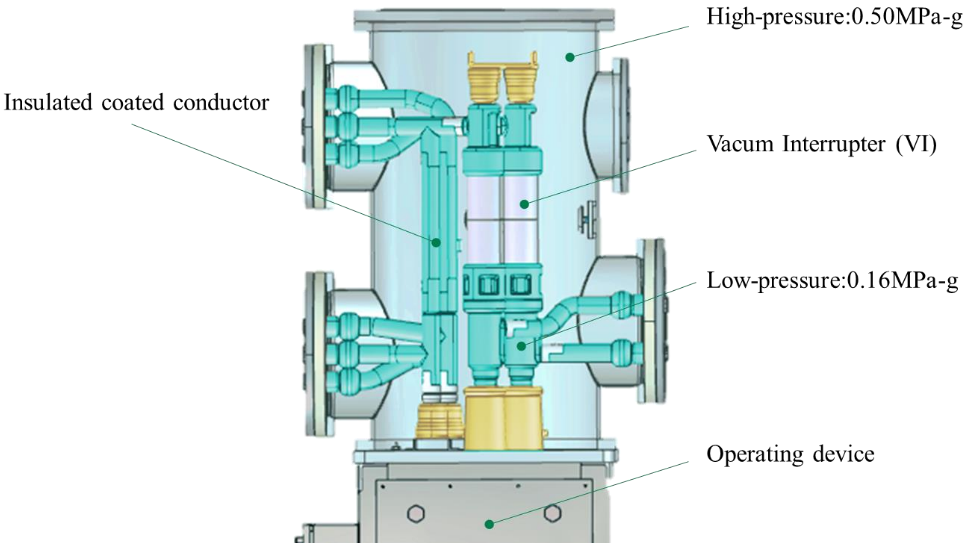

Figure 2: Inner structures of 72/84kV VCB

3.3 Disconnector and Earthing Switch

For disconnectors that are required to bus-transfer current switching, a magnetic field arc-quenching method with a compact magnetic field coil incorporated into the movable contact is used to improve current breaking performance in synthetic air. The high-speed earthing switch, which requires induced current switching, uses a suction type arc-quenching method optimized for the physical characteristics of synthetic air.

As shown in Figure 3, the disconnector and earthing switch are connected by a common movable electrode and operating device via a single drive shaft, thereby simplifying the structure and reducing the number of parts.

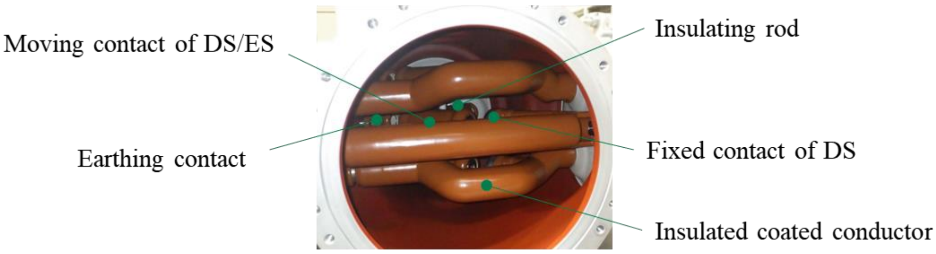

Figure 3: 72/84 kV Disconnector and Earthing Switch

3.4 Metal enclosures (pressure vessel) and conductors

The pressure vessel was designed to prevent rupture of the metal enclosure and the insulating spacers that separate gas compartments. The pressure relief device is employed to protect the cast enclosure and small capacity tank from a sudden pressure increase in the pressure vessel during the main protection fault removal time requires by Japanese power systems. The philosophy of the pressure vessel design is equivalent to that for a conventional SF_6 GIS. Details of verification tests on the operation of the pressure release device are described in chapter 4.2.

To improve insulating and cooling performance, epoxy resin-based paint was applied to the inner conductors as shown in Figure 4. The coating smooths the conductor surface, enabling higher breakdown voltage and lower temperature rise. The paint did not peel or oxidize even when exposed to high temperature, high pressure synthetic air for long time periods - confirming that the coating system can endure more than 30 years in service.

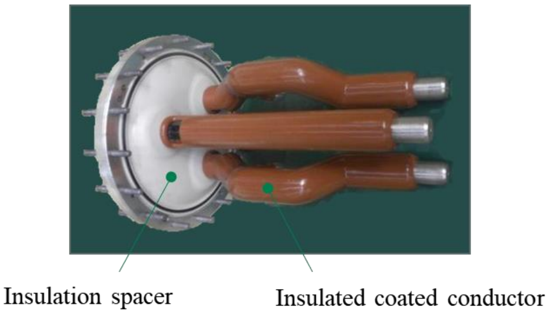

Figure 4: Insulation spacer and insulated coated conductors

3.5 GIS layout and maintainability

In order to meet the needs for expansion and replacement of existing substations, particularly for the commonly narrow and underground substations in Japanese urban areas, the GIS layout was optimized by keeping all three phases within a single enclosure. One fully assembled bay unit can be transported directly by trailer (see Figure 5). The size of the GIS is equivalent to that of existing SF_6 GIS generations to be replaced in the near-term.

The GIS can be optionally equipped with sensors and a diagnostic system in accordance with IEC 61850. These can be linked to condition-based maintenance (CBM) services such as trend analysis and life-time diagnosis through advanced remote monitoring (see Figure 6). Along with accumulated GIS operational know-how and data, advanced CBM systems can reduce maintenance operations and optimize asset management planning.

Figure 5: Transportation tests of the GIS.

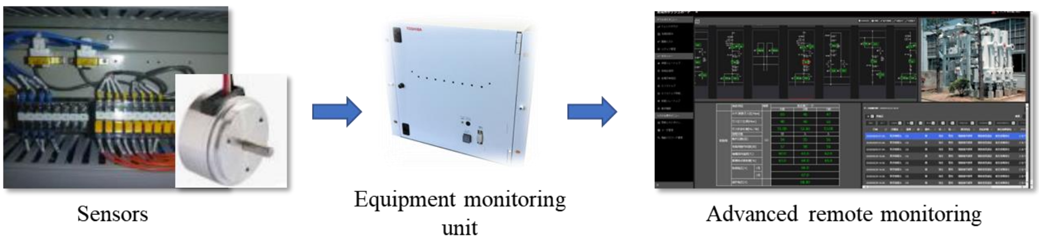

Figure 6: Advanced maintenance systems for GIS

4 Test Results

4.1 Type and verification tests

Type and verification tests were performed in accordance with Japanese GIS standards. The main test items are listed in Table 3. The developed GIS passed all the tests and was confirmed to have sufficient practical performance.

Table 3 Main items of type and verification tests

GIS		Dielectric tests
		Temperature-rise tests
		Short-time withstand current tests
		Partial discharge tests
		Transportation tests
	VCB	Short-Circuit tests
		Short-line fault tests
		Capacitive current switching tests
		Out-of-phase breaking tests
		Transformer limiter fault tests
		Operating and mechanical endurance tests
	DS/ES	Bus transfer current switching tests
		Induced current switching tests
		Small capacitive current switching tests
		Operating and mechanical endurance tests

4.2 Internal arc test

As shown in Figure 7, the setup with a cast enclosure filled with 0.5 MPa-g synthetic air equipped with a pressure relief device (a rupture disk) and a three-phase conductor inside for the DS/ES was tested. An internal arc test was designed to reproduce a three-phase short-circuit fault with a fault current of 31.5 kA that lasts for the standard back-up fault elimination time (1.85 s) for a Japanese power system.

Figure 8 shows the pressure waveforms measured by a pressure sensor mounted inside the tank during the internal arc test. The pressure inside the tank reached 1 MPa-g and the rupture disk operated at approximately 0.02 s. Afterwards, the pressure inside the tank rose to a maximum value of 1.32 MPa-g at about 0.2 s, and then began to decrease while the current was continuously energized, dropping to below 0.5 MPa-g (the rated pressure) at about 0.74 s. After about 1.4 s, it was confirmed that the pressure inside the tank had dropped to the same level as atmospheric pressure. Post-test visual inspection confirmed that the tank had burn-through caused by the ground fault arc, but no rupture or fragmentation of the tank and insulating spacers occurred.

According to the Japanese standard, external effect, which includes burn-through other than the operation of suitable pressure relief device in the enclosure is not permitted during the first 0.5 s of arcing. The present GIS design is proven to have sufficient durability against an internal arc fault for over 1.07 s (much longer than the 0.5 s requirement) based on both the measurement result and calculations.

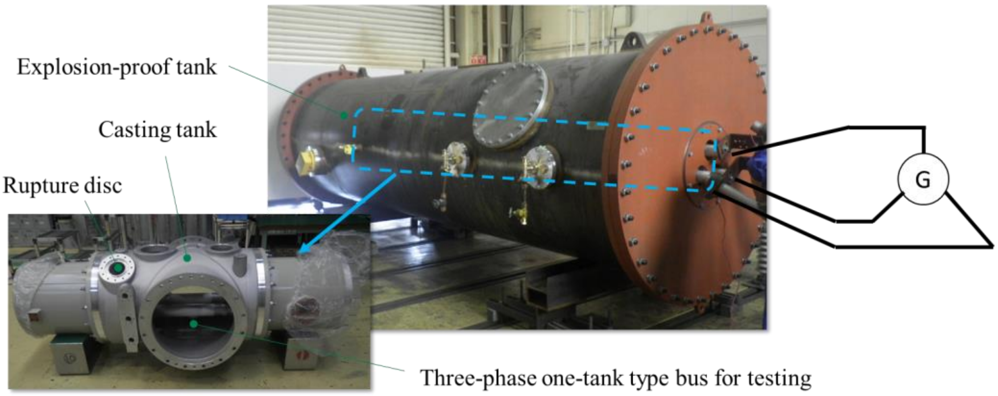

Figure 7: Test object of the internal arc test

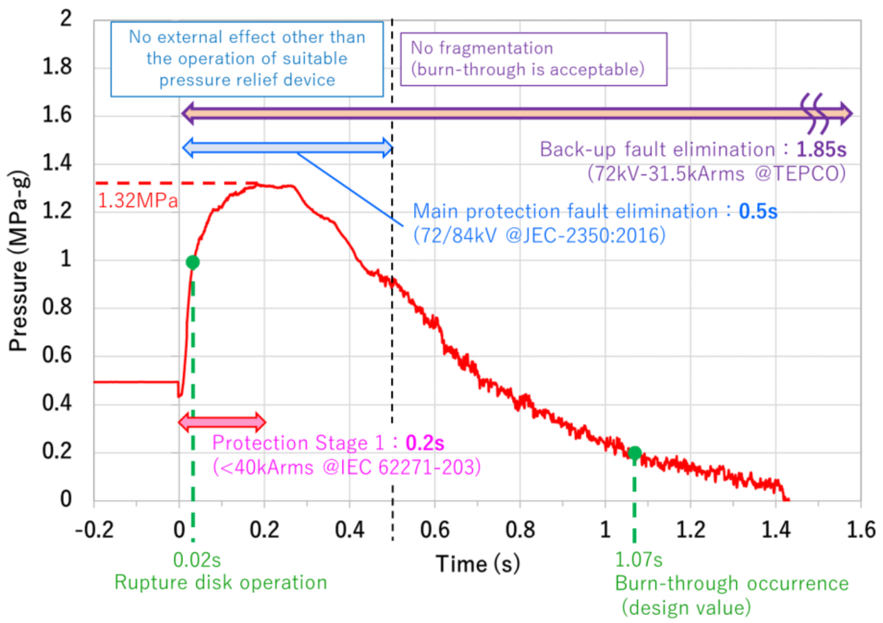

Figure 8: Pressure waveform in the internal arc test

5 Conclusions

An SF_6-free 72/84 kV GIS using natural origin gas was newly developed. It was successfully tested, installed, and energized in February 2023 as the first Japanese pilot substation with a modern SF_6 alternative solution. The present paper reviews the ratings, main features, technologies, and test results. The main points are summarized below:

- To fully comply with the “Seven Requirements” evaluation criteria for SF_6 alternatives developed by the “Japanese SF_6 Alternative Gas Study Group”, it was determined to adopt natural origin gases free from potential risks regarding availability, EHS and regulatory issues that cannot be overcome by design improvement.
- For the circuit breaker, a well-proven vacuum interrupter was adopted for the present GIS. Also, a compact magnetic field arc-quenching method was developed for the disconnector, which is required to switch loop current. A suction type of arc-quenching method optimized for synthetic-air physical characteristics was also developed for the high-speed earthing

switch, which enables inductive current switching since this is one of the more challenging duties for natural origin gases.

- In the GIS design, a compact three-phase encapsulated layout with a vertical circuit breaker and frontal bus bar arrangement was adopted, which enables easy expansion and replacement for existing substations. The present 72/84 kV GIS is sufficiently compact to enable a fully assembled bay to be transported on a single trailer.
- The GIS can be optionally equipped with sensors and a diagnostic system in accordance with IEC 61850. It can be linked to CBM services such as trend analysis and life-time diagnosis through advanced remote monitoring. CBM can contribute to the reduction of maintenance operations and optimal asset management planning.
- Type tests and performance verification tests were performed in accordance with the JEC GIS standards. All tests were successfully passed.
- Internal arc tests were performed to simulate a three-phase short-circuit internal fault. No rupture or fragmentation of the tank and insulating spacer occurred, and the present GIS design is proven to have sufficient durability against an internal arc fault for the standard back-up fault elimination time (1.85 s) for a Japanese power system.
- The first product was successfully installed and energized in February 2023 as the first Japanese pilot substation with a modern SF_6 alternative solution.

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