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# $SF_6$ Gas, A Greenhouse Gas - Possible Replacements

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## SUMMARY

In the 1950s, Westinghouse developed the first circuit breaker, which used Sulphur hexafluoride ($SF_6$) gas as a quenching media. Since then, this technology has been used as insulation in gas insulated switchgear (GIS), gas insulated lines (GIL) and in instrument transformers and insulating and quenching media in high voltage (HV) and medium voltage (MV) circuit breakers.

$SF_6$ gas is known to be a cheap, inert, inorganic, colorless, odorless, non-flammable, and non-toxic gas, which does not react with water and does not react with any material below $50^0C$[1]. $SF_6$ also has an affinity towards negative charges and is known as an electron scavenger because of its high electron attracting behavior. This attraction results in the formation of very slow-moving negative ions which behave like a dielectric in the space between arcing contacts. Due to these electronegative characteristics, $SF_6$ breakers can break, with same conditions, up to 100 times higher current than air breakers. $SF_6$ has a number of properties, for which it is commonly used as a cheap insulating medium. $SF_6$ gas poses no direct risk of water or soil contamination. $SF_6$ equipment has a longer lifetime, has reduced maintenance and is smaller and compacter than other media available [1].

In comparison with the above-mentioned positive characteristics of $SF_6$ gas, $SF_6$ gas presents various negative properties. It is an extremely potent and persistent man-made and naturally occurring greenhouse gas. Although the amount of $SF_6$ gas in atmosphere is minute, its global warming potential is significant. It has 23 500 times higher specific global warming potential than carbon dioxide ($CO_2$) and an atmospheric lifetime of approximately 3200 years, compared to roughly 100 years in the case of $CO_2$ (IPCC 2014) [2]. As a result of these negative properties $SF_6$ gas is one of six gasses listed in the 1997 Kyoto Protocol [3]. In addition, $SF_6$ discharge can produce toxic byproducts, such as $SOF_2$, $SO_2$, HF, $S_2F_{10}$, etc. [4]

This study demonstrates the possible replacements of $SF_6$ equipment with today's existing equipment.



## KEYWORDS

Sulfur hexafluoride, MV and HV electrical equipment, emission reduction, cost


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## 1. Introduction

The atmospheric concentration of $SF_6$ gas has never been higher. Since $SF_6$ is such a stable gas, it has an estimated lifetime of 3200 years. Due to the aforementioned, NTNU (Norwegian University of Science and Technology) professor, Francesco Cherubini has said, "$SF_6$ is considered the most potent chemically reactive gas, investigated by the IPCC." He added, "The concentration of the gas in the atmosphere is increasing so it's good to have some attention on this. However, it is important to put it into context. While $SF_6$ is a dangerous greenhouse gas, $SF_6$ today contributes to less than 1 percent of man-made global warming." The European Union leads the world in the regulation, monitoring and management of $SF_6$ gas. The most recent example is the new regulation on fluorinated greenhouse gasses, Regulation (EU) No 517/2014.
The words of Professor Francesco Cherubini tell us that we have to act on reducing this greenhouse gas impact if it is possible. $SF_6$ gas can be replaced, in many cases, and $SF_6$ gas leaking can be reduced. In the last few years, many manufacturers presented new non-$SF_6$ products. For instance, the use of vacuum circuit breakers (technology known since the 1930s which has been improved with axial magnetic field contact and vacuum furnaces) from 5kV up to 145kV. The vacuum circuit breaker could cover a huge area of $SF_6$ breaker replacement. Using dry air as insulating medium together with vacuum circuit breakers all $SF_6$ gas insulated equipment up to 145kV could be replaced with $SF_6$ gas free equipment. The installation of solid insulated switchgear could replace $SF_6$ gas in GIS up to 46kV and even higher. The installation of $G^3$, a less potent gas in GIL, instrument transformers and hybrid GIS, could replace $SF_6$ gas up to 420kV. GE live tank HV breakers using $G^3$ gas have been recently installed in Europe, and new products in this area can be expected [5].

## 2. Approach for emission reduction

Although most MV ( medium voltage 1-52kV) $SF_6$ equipment is mostly closed sealed equipment (since the early 1980s), for new equipment with a leakage rate of 0.1% and very low emission, the manufacturers (Siemens, Toshiba, Eaton, Meidensha and Hitachi) designed equipment with zero $SF_6$ gas. Siemens and Hitachi upgraded the aforementioned solutions up to 145kV [6,7,8,9,10]. For the higher HV (high voltage) level (230KV and higher), the manufacturers had different approaches. Some manufacturers (e.g. GE) based their design on new gas and some of them (e.g. Siemens) based their design on emission reduction from 0.5% to 0.1%. Considering the factor that GE is not a vacuum bottle manufacturer, GE provided a $G^3$ solution for all HV solutions.
Other gasses which were also supposed to replace $SF_6$ gas have been shown to be unstable as a dielectric and arc quenching media. $G^3$ is known as a green gas for grid and was developed in collaboration between GE and 3M company. $G^3$ is a gas mixture that is composed of $C_4F_7N$ (Novec™ 4710), $CO_2$. Since 2014 GE started testing $G^3$ showed the following [11,12,13]:

- High-dielectric strength
- Good arc quenching capability
- Low dew point
- Nonflammable and nonexplosive
- Compatibility with other materials

In addition to this:

- Low global warming potential (GWP)
- No ozone depletion potential (ODP)
- Nontoxic and nontoxic byproducts

## 3. MV and HV up to 145kV circuit breakers for outdoor application

All MV and HV circuit breaker $SF_6$-free solutions up to 145kV are based on vacuum Interrupters. Older vacuum breaker solutions, considering that the interrupters with nominal voltages higher than 36kV require additional outside insulation, in many cases were based on $SF_6$ gas insulation and this insulation need a $SF_6$ gas free replacement e.g. dry air (clean air) insulation.

### 3.1 Outdoor live tank (dominant in Europe) circuit breakers up to 36kV replacement

The image below shows a live tank ABB breaker, which can be either $SF_6$ or vacuum. Inside the insulator is either an $SF_6$ interrupter with a Polytetrafluoroethylene (PTFE) nozzle or a vacuum interrupter. Energoinvest, in 1989, designed a similar $SF_6$ live tank breaker for the Malaysian market. Energoinvest breakers, after they reach the end of lifetime, can be replaced with vacuum circuit breakers from other manufacturers, e.g. ABB or Siemens. Vacuum breakers have a smaller and less expensive operating mechanism, which can lead to overall lower total costs, proving their potential to benefit hydro companies.

**Figure 1.** ABB 36kV $SF_6$ and vacuum live tank circuit breaker (courtesy of ABB).

The overvoltages which could be caused by MV and HV vacuum circuit breaker switching could be properly analyzed and controlled by surge arrestors and surge capacitors [14].

### 3.2 MV metalclad or gas insulated switchgear

Nowadays most breakers inside MV metalclad and GIS are vacuum breakers, either with a motor spring or magnetic actuator. In MV switchgear $SF_6$ gas was used as an insulation media to make a MV switchgear smaller and more compact. However, the global warming $SF_6$ gas effect forced manufacturers to develop other MV switchgear design. New demands for new green metalclad switchgear which will be installed for distributed generation (solar and wind) also forced manufacturers to provide a new solution. The metalclad switchgear manufacturers such as Toshiba, Eaton, Schneider, etc. designed solid insulated switchgear. For the time being Siemens is offering its modular 8DN8 switchgear and $SF_6$ gas is replaced with dry air. All of these designs are also applicable in high pollution areas.

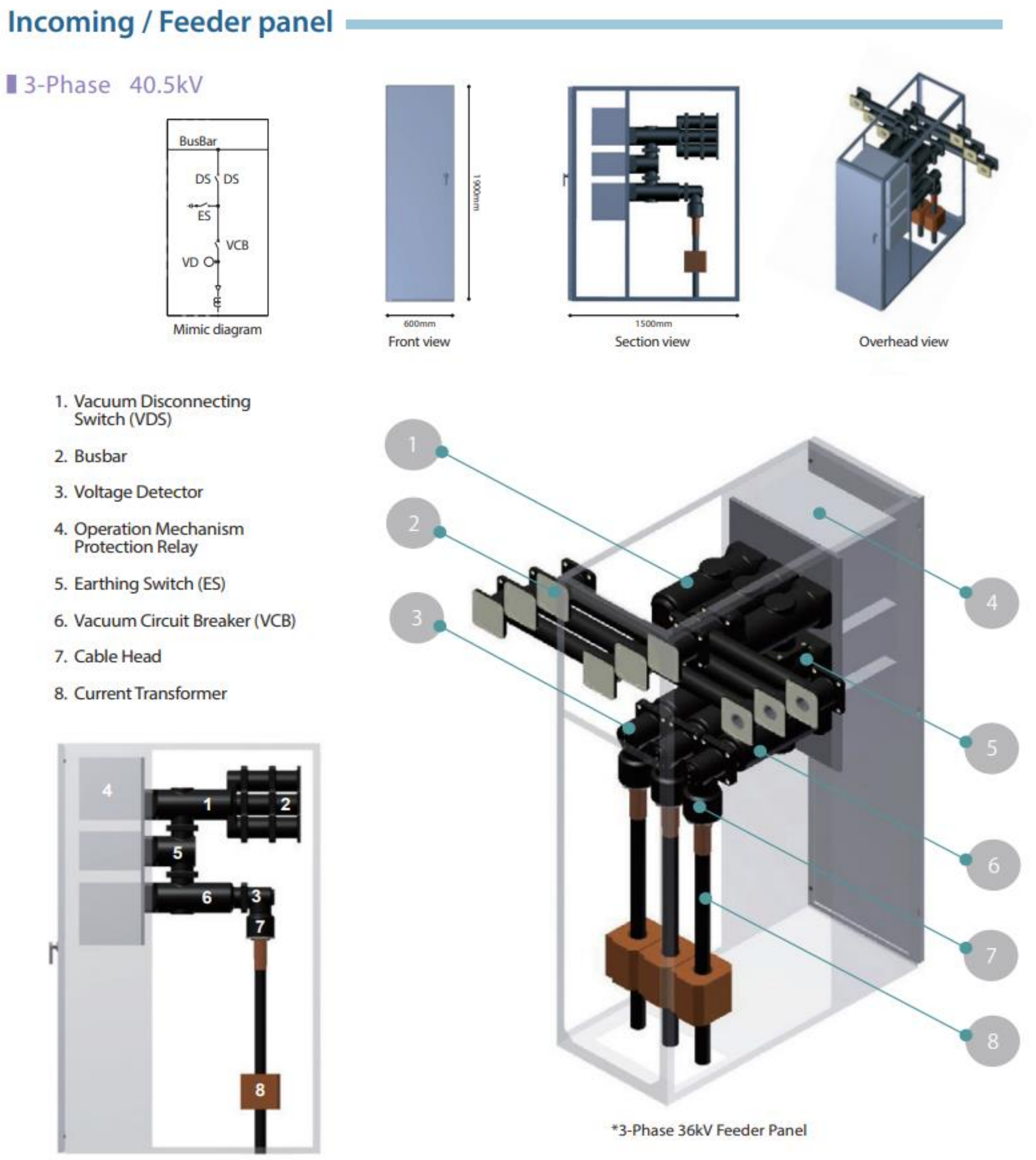



**Figure 2.** Toshiba solid insulated switchgear (Toshiba catalogue)

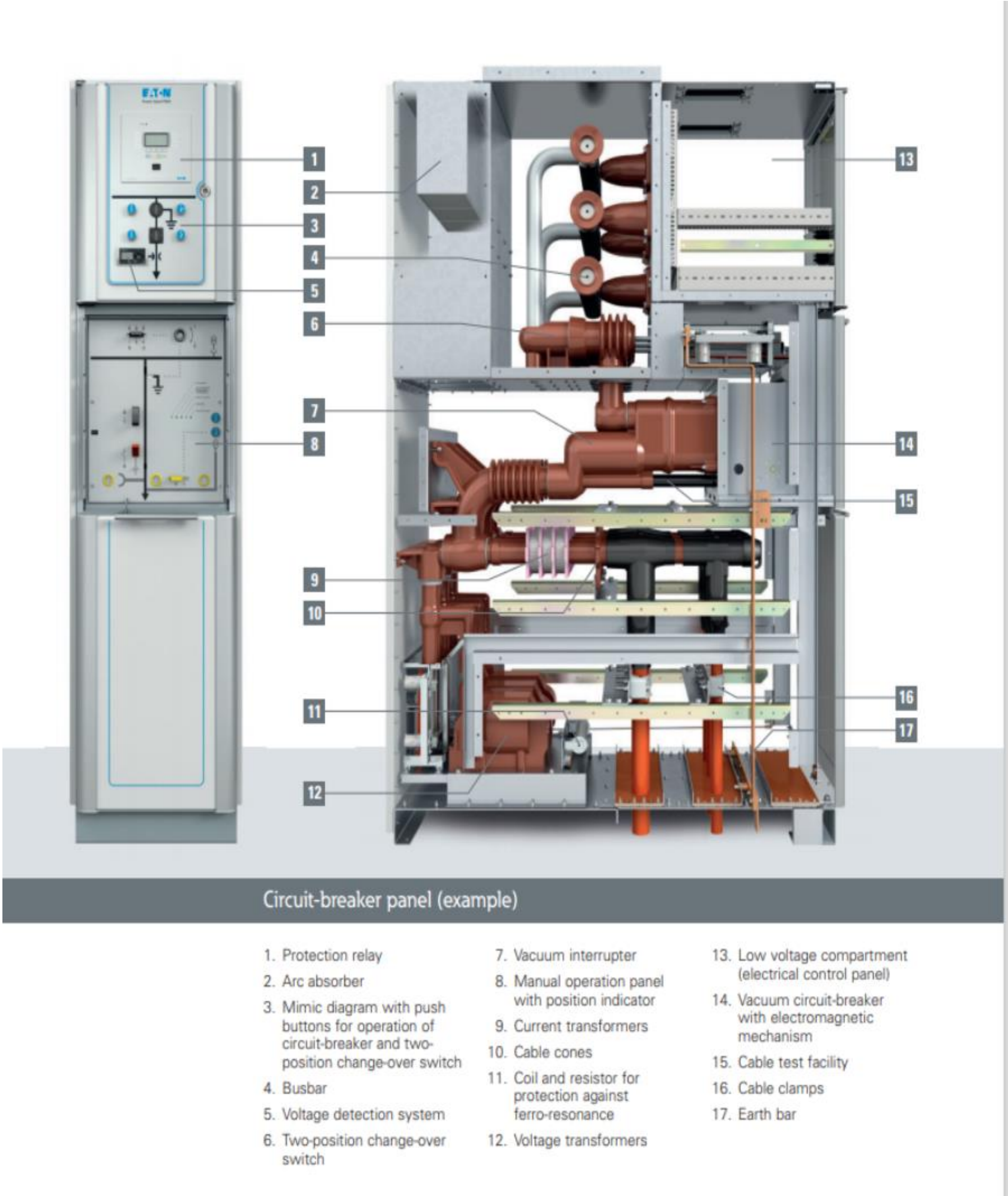
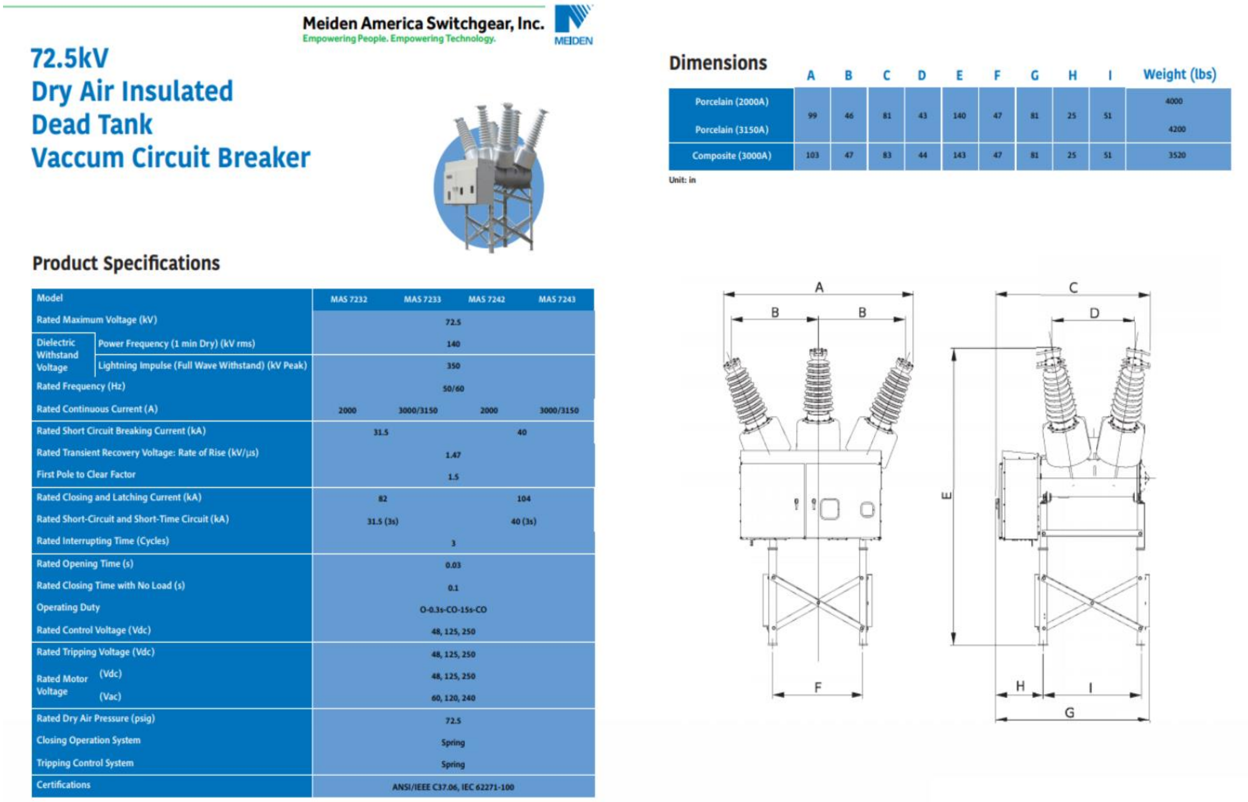



**Figure 3.** Eaton Solid Insulated Switchgear (Eaton catalogue)

The solid insulation switchgear uses epoxy insulation to encapsulate all live parts such as busbars, vacuum interrupters, disconnect switches, ground switches, cable terminations etc. The live parts are covered with a molded epoxy layer, which is then covered with a grounded conductive layer. The outside grounded conductive layer reduces electric field strength inside the switchgear. This grounded layer also protects switchgear from phase to phase fault as well.

### 3.3 Vacuum circuit breaker with dry air insulation up 145KV

Dry air is the insulating medium which has been used for decades for MV application. With the development of HV vacuum interrupters, dry air became applicable for dead tank circuit breakers and dry air insulated switchgear. **Figure 4** and **Figure 5** show Hitachi and Meidensha dead tank dry air insulated vacuum circuit breakers. Hitachi circuit breakers up to 72.5kV, 2000A and 31.5kA do not require dead tank heaters on -50°C, what was impossible for any MV $SF_6$ dead tank circuit breaker. Considering that Siemens developed 145kV dry air insulated live tank vacuum circuit breakers 3AV1 and 145kV dry air insulated switchgear with vacuum circuit breaker 8VN1 blue GIS in **Figure 6**. In the near future, a Siemens new product e.g. dry air dead tank vacuum circuit breaker, could be anticipated.




| Model | MAS 7232 | MAS 7233 | MAS 7242 | MAS 7243 |
|---|---|---|---|---|
| Rated Maximum Voltage (kV) | 72.5 | | | |
| Dielectric Withstand Voltage: Power Frequency (1 min Dry) (kV rms) | 140 | | | |
| Dielectric Withstand Voltage: Lightning Impulse (Full Wave Withstand) (kV Peak) | 350 | | | |
| Rated Frequency (Hz) | 50/60 | | | |
| Rated Continuous Current (A) | 2000 | 3000/3150 | 2000 | 3000/3150 |
| Rated Short Circuit Breaking Current (kA) | 31.5 | | 40 | |
| Rated Transient Recovery Voltage: Rate of Rise (kV/µs) | 1.47 | | | |
| First Pole to Clear Factor | 1.5 | | | |
| Rated Closing and Latching Current (kA) | 82 | | 104 | |
| Rated Short-Circuit and Short-Time Circuit (kA) | 31.5 (3s) | | 40 (3s) | |
| Rated Interrupting Time (Cycles) | 3 | | | |
| Rated Opening Time (s) | 0.03 | | | |
| Rated Closing Time with No Load (s) | 0.1 | | | |
| Operating Duty | O-0.3s-CO-15s-CO | | | |
| Rated Control Voltage (Vdc) | 48, 125, 250 | | | |
| Rated Tripping Voltage (Vdc) | 48, 125, 250 | | | |
| Rated Motor Voltage (Vdc) | 48, 125, 250 | | | |
| Rated Motor Voltage (Vac) | 60, 120, 240 | | | |
| Rated Dry Air Pressure (psig) | 72.5 | | | |
| Closing Operation System | Spring | | | |
| Tripping Control System | Spring | | | |
| Certifications | ANSI/IEEE C37.06, IEC 62271-100 | | | |

| Dimensions | A | B | C | D | E | F | G | H | I | Weight (lbs) |
|---|---|---|---|---|---|---|---|---|---|---|
| Porcelain (2000A) | 99 | 46 | 81 | 43 | 140 | 47 | 81 | 25 | 51 | 4000 |
| Porcelain (3150A) | | | | | | | | | | 4200 |
| Composite (3000A) | 103 | 47 | 83 | 44 | 143 | 47 | 81 | 25 | 51 | 3520 |

Unit: in

**Figure 4.** Meidensha dry air insulated dead tank vacuum circuit breaker (Meidensha catalogue)

Siemens clean air design is similar to 8DN9 $SF_6$ design and it looks like that many existing parts from 8DN9 were modified and used for 145kV blue GIS.

**Figure 5.** Hitachi 72.5kV dry air insulated dead tank vacuum circuit breaker

## Gas-Insulated Switchgear
## Type 8VN1 blue up to 145 kV / 40 kA

**Technical data**

| Switchgear type | 8VN1 | |
|---|---|---|
| Rated voltage | up to | 145 kV |
| Rated frequency | | 50 / 60 Hz |
| Rated short-duration power-frequency withstand voltage (1 min) | up to | 275 kV |
| Rated lightning impulse withstand voltage (1.2 / 50 µs) | up to | 650 kV |
| Rated continuous current – busbar | up to | 3150 A |
| Rated continuous current – feeder / bus coupler | up to | 3150 A |
| Rated short-circuit breaking current | up to | 40 kA |
| Rated peak withstand current | up to | 108 kA |
| Rated short-time withstand current (up to 3 s) | up to | 40 kA |
| Leakage rate per year and gas compartment (type-tested) | | < 0.1 % |
| Driving mechanism of circuit-breaker | | stored-energy spring |
| Rated operating sequence | | O-0.3 s-CO-3 min-CO<br>CO-15 s-CO |
| Interrupter technology | | Vacuum |
| Insulation medium | | Clean air |
| Weight of $SF_6$ or other flourinated greenhouse gases | | 0 kg |
| GWP Global Warming Potential | | 0 |
| $CO_2$ equivalent | | 0 kg |
| Rated filling pressure | | 0,79 MPa abs |
| Bay width common pole drive | | 1000 mm |
| Bay hight, depth (depending on bay arrangement) | | 3200 mm x 5500 mm |
| Bay weight (depending on bay arrangement) | | 4,7 t |
| Ambient temperature range | | -50 °C up to +55 °C |
| Installation | | indoor / outdoor |
| First major inspection | | > 25 years |
| Expected lifetime | | > 50 years |
| Standards | | IEC / IEEE |

Other values on request

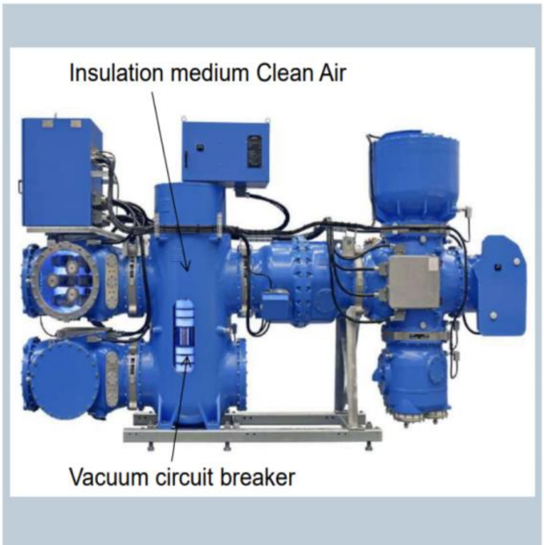



**Figure 6.** Siemens 145kV clean air GIS (Siemens presentation)

**3.4 G$^3$ (green gas for grid) for 230kV and higher voltages**

As mentioned prior, $SF_6$ free electrical equipment, is based on the improvement of the existing technologies, but G$^3$ gas is a new technology which exists since 2014. Many manufacturers tried to find a gas or gas mixture which could replace $SF_6$ gas, however, these trials have many times finished unsuccessful, the gas/gas mixture which was tested showed unstable dielectric and arc quenching characteristics. G$^3$ is a mixture compound of three gasses fluoronitrile $C_4F_7N$ (Novec™ 4710), $CO_2$ and $O_2$. The mixture has 99% lower impact on global warming than $SF_6$. Each of these components has its own purpose [12,13,14]:

- The fluoronitrile provides dielectric strength to the gas mixture thanks to nitrile triple bond combined with fluorine
- $CO_2$ handles the arc quenching process
- Oxygen plays major role in the gas chemical decomposition especially in case of a heavy arc interruption.

The first GE $SF_6$-free G$^3$ 420kV GIL went line in June 2016 at Sellindge, South of England, **Figure 7**.

**Figure 7.** GE – 420kV G$^3$ GIL solution at National Grid substation in Sellindge, UK

Tested and available G$^3$ products are live tank circuit breaker and GIS up to 145kV (both) and GIL up to 420kV. Considering that GIS and live tank circuit breakers up to 145kV are covered with dry air/ clean air insulation and vacuum circuit breakers, the development of 245kV circuit breakers and GIS can be expected [12,13,14,15, 16,17].

## 4. Conclusion

Through the assessment of available $SF_6$ free equipment up to 420kV, the study has highlighted future directions. This paper brings to light that $SF_6$ free equipment up to 145kV is on the market. Some countries have traditionally relied on $SF_6$ insulated equipment, including France, Sweden, Bosnia and Herzegovina and some North American states and provinces. In the listed regions, the percentage of the equipment that can be replaced with existing $SF_6$ free products is approximately 60-70%. Laboratory tests of G$^3$ gas insulated equipment show that G$^3$ gas is verified as the most eco-friendly $SF_6$ gas replacement for voltages 230kV and higher. In the future, more G$^3$ insulated equipment for higher voltages and lower temperatures (the present solution tested on -20°C), could be expected.

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