TECHNICAL WHITE PAPER

HMP-WP-2603

The Path Away from SF_6: From Alternative-Gas Research to Eco-Friendly Switchgear

Which alternative gases were tested, and how do they compare with SF_6?

ABSTRACT

Sulfur hexafluoride (SF_6) has been the insulating and arc-quenching medium of power switchgear for more than half a century, a position attributable to its exceptional dielectric strength and arc-interruption capability. It is also one of the most potent greenhouse gases known, with a 100-year global warming potential (GWP-100) of approximately 23,500 relative to CO_2. Reducing dependence on SF_6 without compromising equipment performance has accordingly become a central problem for the power industry over the past two decades. This paper reviews the successive attempts to replace SF_6 — natural gases, early halocarbons, and the fluoronitrile and fluoroketone gases introduced since the 2000s — together with the alternative technical route in which current interruption is delegated to a vacuum interrupter while air or nitrogen performs insulation. It compares the dielectric strength, boiling, liquefaction or sublimation temperature, GWP and engineering characteristics of each medium, assesses the merits and application boundaries of the two routes, and examines the medium-voltage transition in which vacuum interruption compensates for the limited arc-quenching capability of environmentally benign gases. The history and regulatory framework of SF_6 are treated in HMP-WP-2601 and HMP-WP-2602 respectively.

1 Background: Why SF_6 Must Be Replaced

In medium-voltage switchgear — gas-insulated switchgear (GIS) and ring main units — and in circuit breakers, SF_6 performs two functions. As an insulating medium its dielectric strength is approximately 2.5 times that of air; as an arc-quenching medium it interrupts the high-temperature arc of making and breaking operations far more effectively than air or oil. These two properties established it as the standard solution of the power industry from the middle of the 20th century onward.

SF_6 also carries an equally significant environmental burden. Its 100-year global warming potential (GWP-100) is approximately 23,500 and its atmospheric lifetime approximately 3,200 years, so that each kilogram released produces a long-term warming effect equivalent to several tens of thousands of kilograms of CO_2, and the gas is effectively non-degradable in the atmosphere. After SF_6 was listed under the 1997 Kyoto Protocol, European and North American regulators progressively tightened limits on its use and emission. Regulation (EU) 2024/573, adopted in 2024, is more direct: from 1 January 2026, medium-voltage switchgear rated at 24 kV and below may not be placed on the market; from 2030 the same applies to equipment rated 24–52 kV, and from 2032 to equipment above 52 kV. For switchgear rated 52–145 kV with a rated short-circuit breaking current not exceeding 50 kA and a GWP of 1 or above, the restriction has been brought forward to 2028; this 2028 date applies only to that specific subclass (breaking current ≤ 50 kA and GWP ≥ 1), while the 2032 date above remains the general deadline for other equipment rated above 52 kV. The California Air Resources Board (CARB) has likewise, under its amended Regulation for Reducing Sulfur Hexafluoride Emissions from Gas Insulated Switchgear (17 CCR §§95350–95359), progressively prohibited the procurement of new gas-insulated equipment containing SF_6, with acquisition bans phasing in from 2025 [14].

The difficulty of substitution lies in the fact that an acceptable alternative must satisfy a demanding set of requirements simultaneously — dielectric strength, arc-quenching capability, low or zero GWP, non-toxicity and non-flammability, operability at low temperature, and material compatibility. This is why the search has repeatedly had to change direction. Medium voltage is the focus of this paper because substitution technology is most mature at this level, EU regulation takes effect there first, and it is the principal arena of the global transition away from SF_6.

2 Two Substitution Routes: Gas Substitution and Technical Substitution

Two technical routes have emerged in engineering practice.

Route A — gas substitution: the identification or synthesis of a new insulating or arc-quenching gas that directly replaces SF_6. This was long the mainstream of research, from natural gases through the early halogenated and fluorocarbon gases to the fluoronitrile and fluoroketone gases introduced since the beginning of this century.

Route B — technical substitution: removing the dependence on the gas for current interruption by delegating interruption to a vacuum interrupter and leaving air or nitrogen to perform insulation only, so that the overall GWP becomes zero. Vacuum interruption is the principal means of compensating for the limited arc-quenching capability of environmentally benign gases: such gases are generally inferior to SF_6 in arc quenching, whereas vacuum interrupters are a mature technology with high breaking capability and no maintenance requirement, and the combination is now an established solution.

The two routes converge and coexist at medium voltage, each with its own application domain; they represent, respectively, incremental improvement and a more fundamental substitution.

3 Alternative Gases and Performance Comparison

3.1 Natural gases: air, nitrogen and carbon dioxide

The first candidates were the naturally occurring gases, which are abundant and environmentally benign. In electrical terms the dielectric strength of air is approximately 0.43–0.5 that of SF_6. It should be noted that natural (ambient) air and dry air exhibit essentially the same relative dielectric strength: the insulating behaviour of air is governed by its nitrogen and oxygen content, and the influence of moisture at ambient temperature is limited, so the two may be treated as the same class of medium for electrical purposes. Some manufacturers use dry air, dehumidified and with a controlled dew point, as the insulating medium; the ASNA atmospheric-sealed concept of HM Power uses natural air.

Nitrogen has a dielectric strength of approximately 0.38 that of SF_6 and carbon dioxide approximately 0.35. The boiling or liquefaction temperatures of all three are low (approximately -194 °C for air, -196 °C for nitrogen, and -78.5 °C, at which CO_2 sublimes at atmospheric pressure), and their GWP is zero or very low, that of CO_2 being 1 by definition. As insulating media they are environmentally benign, suited to low temperatures and inexpensive, but their dielectric strength is only about one third that of SF_6, so a substantially higher pressure or a larger insulation distance is required to withstand the same voltage; their arc-quenching capability is also weak, and current interruption generally has to be delegated to a vacuum interrupter.

These natural gases are thus of low dielectric strength, yet with elevated pressure, optimised insulation geometry and a vacuum interrupter they meet the insulation and switching requirements of medium-voltage equipment. Precisely because their GWP is zero and no filling or recovery management is needed, they are the preferred insulating media of the vacuum-plus-air approach.

3.2 Early synthetic gases: attempts and abandonment

The halogenated and fluorocarbon gases tested in the early period, such as the refrigerants R12 and R134a, reach a relative dielectric strength of 0.85–0.90 that of SF_6, but were not adopted in power equipment because of their high GWP, their toxicity, or their severe liquefaction at low temperature. R12 in particular is a chlorofluorocarbon (CFC) with a high ozone depletion potential; it was phased out under the Montreal Protocol as early as the 1990s and is not permissible as a power-insulation medium under current regulation. The lesson of this episode is that dielectric equivalence alone is insufficient: environmental acceptability, safety and low-temperature engineering feasibility must be satisfied simultaneously, which raises the threshold for substitution considerably.

3.3 Next-generation synthetic gases: fluoronitriles and fluoroketones

Since the beginning of this century, chemical manufacturers have developed two families of synthetic gases intended to combine adequate dielectric performance with environmental acceptability.

Fluoronitrile — perfluoroisobutyronitrile (C_4F_7N, 3M Novec 4710): developed by 3M and introduced to the power industry around 2014. Its GWP is approximately 2,100 and its atmospheric lifetime approximately 30 years, far below those of SF_6, but its liquefaction temperature at atmospheric pressure is approximately -4.7 °C, so it must be used in mixture with CO_2, N_2 or dry air. The g^3 gas, Green Gas for Grid, comprising approximately 5% C_4F_7N and 95% CO_2, introduced by GE, now GE Vernova, in August 2014 is an example: its GWP is more than 99% below that of SF_6, and it operates at ambient temperatures down to approximately -30 °C.

Fluoroketone — perfluoro ketone ($C_5F_{10}O$, 3M Novec 5110, the principal constituent of AirPlus): developed by ABB with 3M and introduced in 2015. In pure form its dielectric strength is high and its GWP below 1, but its boiling point is approximately 26.9 °C, so it must be mixed with dry air or CO_2; the condensation temperature of AirPlus is approximately -25 °C.

Both families share the advantage of dielectric performance close to that of SF_6 and a very low GWP, which allows compact gas-insulated designs to be retained. They also share the disadvantages of a high boiling or liquefaction temperature, requiring heating, pressurisation or a buffer gas at low ambient temperature; proprietary compositions and comparatively high cost; a GWP that is low but not zero; and arc decomposition products and long-term material compatibility that still require continued assessment.

In arc-quenching capability SF_6 remains superior, followed by the g^3 fluoronitrile mixture, while CO_2–O_2 mixtures are comparatively weak. Interrupting load current in medium-voltage equipment with an environmentally benign synthetic gas therefore generally requires dedicated design, whereas a vacuum interrupter provides reliable interruption comparable with, or better than, conventional solutions. This is the technical basis on which vacuum-plus-air has spread at medium voltage.

3.4 Comparative performance

For direct comparison, Table 1 summarises the relative dielectric strength, boiling, liquefaction or sublimation temperature, GWP-100 and principal characteristics of SF_6 and the alternative media; Figure 1 presents the dielectric strength differences as a bar chart, and Figure 2 the order-of-magnitude GWP differences on a logarithmic scale.

Table 1 Key parameters of SF_6 and principal alternative insulating media (compiled from public technical literature; SF_6 and CO_2 as sublimation points at atmospheric pressure, others as boiling or condensation points)

Medium	Relative dielectric strength (vs SF_6)	Boiling/ liquefaction/ sublimation point (°C)	GWP-100	Key characteristics
SF_6	1.0	-64	23,500	Reference: best combination of insulation and arc quenching, but extremely high GWP
g^3 (C_4F_7N/CO_2 mixture)	≈0.75–0.95	usable down to -30 °C as a mixture	≪100 (over 99% below SF_6)	Near-SF_6 dielectric strength, compact, requires gas mixture
C_4F_7N (fluoronitrile, pure)	high	-4.7	≈2,100	Lower GWP, but high liquefaction point; must be mixed with CO_2/N
AirPlus ($C_5F_{10}O$ / dry air)	≈0.7–0.8	condensation ≈ -25	<1	Fluoroketone mixture; good dielectric performance, near-zero GWP
$C_5F_{10}O$ (fluoroketone, pure)	≈2.1	26.9	<1	Highest dielectric strength but high boiling point; cannot be used alone at atmospheric pressure
Air (natural / dry air)	≈0.43–0.5	-194	0	GWP = 0, abundant, suited to low temperature; weak dielectric strength
N_2 (nitrogen)	≈0.38	-196	0	GWP = 0; weak dielectric strength; buffer or insulating gas
Co_2 (carbon dioxide)	≈0.35	-78.5	1	Weak dielectric strength; can serve as buffer gas

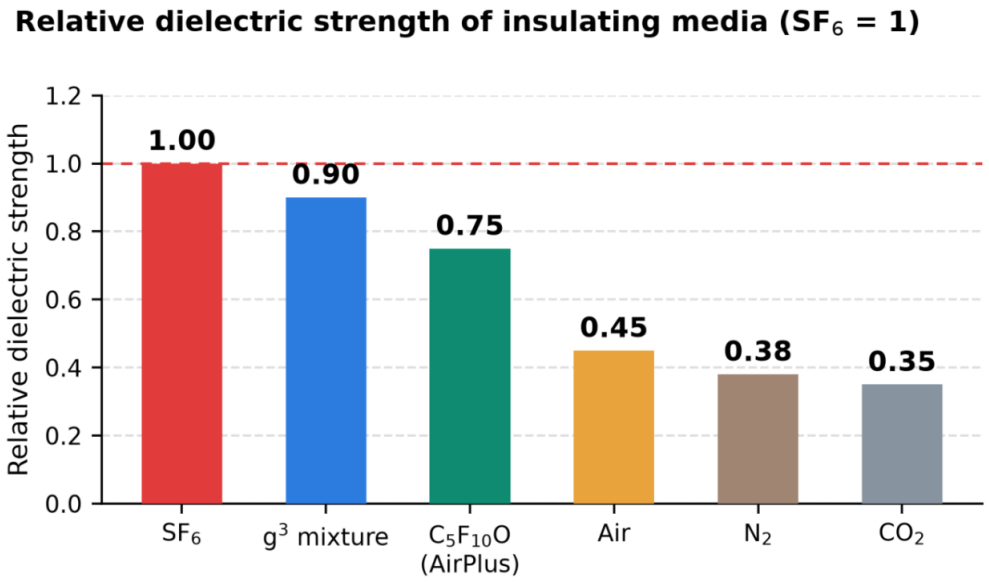


Figure 1 — Relative dielectric strength of insulating media (SF_6 = 1)

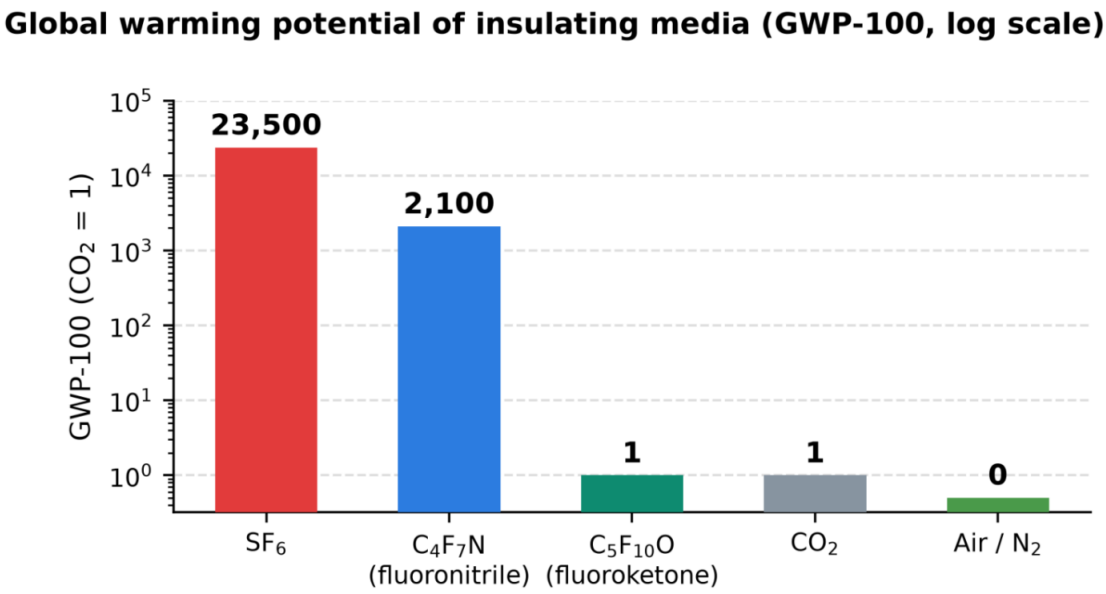


Figure 2 — Global warming potential of insulating media (GWP-100, logarithmic scale)

4 Medium-Voltage Evolution: From Gas Substitution to Vacuum-plus-Air

Medium voltage, and the 12–52 kV range in particular, is where substitution technology has been most widely deployed, and its evolution has passed through three phases. In the first, pure SF_6 GIS dominated: equipment was compact and performance excellent, but emissions and the associated environmental burden were substantial. In the second, from the beginning of this century, GIS using environmentally benign synthetic gases (g^3, AirPlus and others) entered commercial service, with GWP below 1 and compact gas-insulated dimensions retained, at the cost of the heating or pressurisation demanded by the higher boiling points. The third phase, now becoming established, delegates interruption to a vacuum interrupter and insulation to air or nitrogen, achieving the most complete substitution with a GWP of zero. Figure 3 illustrates this evolution.

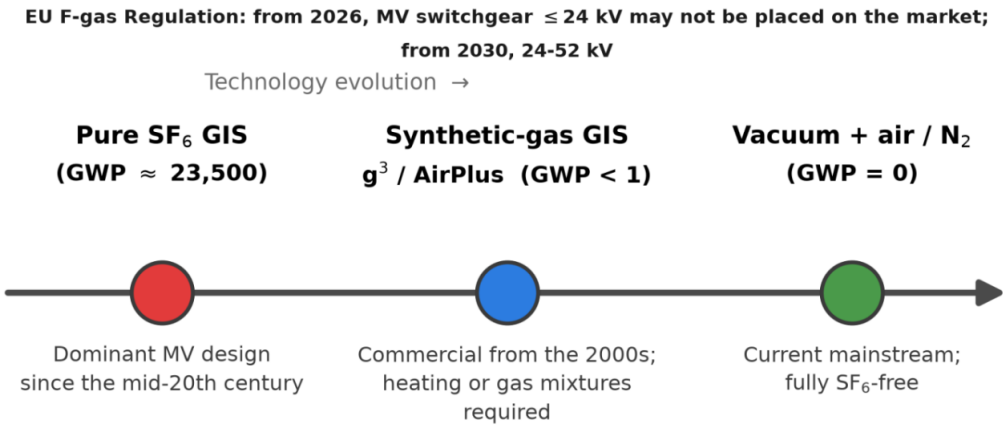


Figure 3 — Evolution of SF_6-free medium-voltage technology, with EU regulatory milestones

Why has vacuum-plus-air become the mainstream at medium voltage? For four reasons: its GWP is zero, eliminating greenhouse gas emissions at source; the technology is mature and reliable, vacuum interruption having several decades of engineering record; it satisfies the market-access threshold of the EU F-gas Regulation, under which medium-voltage equipment at or below 24 kV may not be placed on the market from 2026; and it requires no filling, recovery or leakage management for SF_6 and no heating at low ambient temperature. Environmentally benign synthetic gases remain in use where equipment volume is tightly constrained and a higher dielectric level is required. In medium-voltage primary distribution, air-insulated switchgear (AIS) still accounts for a substantial share of the market, varying widely by region between approximately 40% and 80%.

Ring main units and similar medium-voltage secondary distribution equipment — small, numerous and deployed throughout urban and rural networks — are among the most intensive users of SF_6. It is at this voltage level that the EU F-gas Regulation first imposes limits, obliging manufacturers to convert their medium-voltage lines to SF_6-free designs; ABB, Schneider Electric and HM Power have introduced medium-voltage SF_6-free ranges combining air insulation with vacuum interruption as direct replacements for conventional SF_6 ring main units.

By voltage class, vacuum-plus-air, or nitrogen, insulation has become the mainstream solution for secondary distribution at or below 24 kV, while primary distribution at 24–52 kV shows a parallel pattern in which vacuum-plus-air and environmentally benign synthetic gases coexist; the choice depends on footprint, environmental and cost constraints.

5 Merits and Limitations of the Principal Solutions

5.1 Vacuum interruption with air or nitrogen insulation

This is the most widely adopted SF_6-free solution at medium voltage: a vacuum interrupter performs interruption while air or nitrogen serves only as the insulating medium, so that the overall GWP is zero. Its merits are complete environmental compatibility, no gas leakage or recovery burden, suitability for low temperatures, and comparatively simple maintenance. Its limitations are equally clear: the low dielectric strength of air and nitrogen requires a larger gas volume or a higher pressure to meet insulation requirements; interruption depends entirely on the vacuum interrupter, which is not recognised by IEC standards as a disconnecting switch, so a disconnector is normally connected in series, adding mechanical and cost complexity. Nevertheless the solution is widely commercialised in the medium-voltage ranges of ABB, Schneider Electric and other manufacturers, and fully satisfies the requirements of the EU F-gas Regulation.

HM Power was among the first to apply atmospheric-sealed natural air insulation (ASNA) to medium-voltage ring main units, covering the 12–24 kV range. By optimising the electric field distribution inside the enclosure and using natural air at atmospheric pressure as the substitute for SF_6, the design requires no gas filling, no gauge pressure and no leakage; its footprint is comparable to that of a pressurised dry-air enclosure, while pressure monitoring is eliminated and maintenance-free operation of approximately 40 years is achieved. The technology is covered by more than one hundred Chinese and foreign patents; the products are certified by TÜV and KEMA and comply with CE requirements and Regulation (EU) 2024/573; these performance and certification figures are manufacturer data. The development of ASNA is described in HMP-WP-2606.

5.2 Environmentally benign synthetic gases (g^3, AirPlus and similar)

The synthetic-gas approach seeks to retain the compactness of GIS while substantially reducing GWP. With g^3, a C_4F_7N/CO_2 mixture, as the representative case, dielectric performance approaches that of SF_6 and GWP is more than 99% lower; the GWP of AirPlus, $C_5F_{10}O$ in dry air, is below 1. The merits are a high dielectric level and the possibility of reusing mature GIS designs and compact footprints. The limitations are the high boiling point, which requires heating or pressurisation and a buffer gas at low ambient temperature; proprietary compositions that raise cost; a GWP that is low but not zero; and arc decomposition products and material compatibility that still require long-term verification. The approach is used mainly at high and extra-high voltage and in applications where footprint is critical.

5.3 CO_2 mixtures and solid insulation

Pure CO_2 or CO_2–O_2 mixtures can be used from medium to high voltage; their dielectric strength is approximately 35%–40% that of SF_6 and their arc-quenching capability is weaker than that of g^3, so they are generally applied where requirements are moderate or cost is sensitive. Solid insulation, such as cast epoxy resin, serves as a supplementary means in specific space-constrained applications, but its range is limited because inspection and heat dissipation in service are difficult.

On balance, environmental completeness, dielectric performance, compactness, cost and maturity cannot all be maximised at once: vacuum-plus-air is the most complete environmentally, while synthetic gases offer advantages in performance and footprint. The choice must be made against voltage class, climatic conditions and whole-life cost.

6 Conclusions and Trends

Reviewing the course of substitution, the industry has moved from the search for a single ideal replacement gas to a portfolio of techniques deployed in combination as required. At medium voltage, vacuum interruption with air insulation is becoming the mainstream SF_6-free choice; at high and extra-high voltage, synthetic gases such as g^3 continue to advance. Regulation (EU) 2024/573 is unquestionably the decisive driver, having elevated SF_6-free design from a technical option to a condition of market access. As regulation takes effect and costs fall, SF_6-free equipment can be expected to become the default choice for new power equipment, and the question of the replacement gas that has occupied the industry for decades will be answered by a combination of techniques rather than by a single medium.

7 Key Takeaways

1. SF_6 performs both the insulation and the arc-quenching function; its dielectric strength is approximately 2.5 times that of air and its interrupting capability far exceeds that of air or oil. Its GWP-100 of approximately 23,500 and atmospheric lifetime of approximately 3,200 years make it a priority target of global control.
2. Substitution has followed two routes: gas substitution, that is, identifying or synthesising a new gas to replace SF_6; and technical substitution, that is, vacuum interruption combined with air or nitrogen insulation, with a GWP of zero.
3. Natural gases, air, N_2 and CO_2, are environmentally complete but have a dielectric strength of only about one third that of SF_6 and must be combined with a vacuum interrupter; the early halogenated and fluorocarbon gases were abandoned because of environmental, safety or low-temperature deficiencies.

4 Next-generation synthetic gases, g^3 and AirPlus, approach the dielectric performance of SF_6 with a much lower GWP, but they remain fluorinated media with a non-zero GWP, require heating or pressurisation at low temperature, carry proprietary costs, and have arc decomposition products that remain to be verified.

5 Vacuum interruption is the established means of compensating for the limited arc-quenching capability of environmentally benign gases. At medium voltage, vacuum interruption with air or nitrogen insulation is becoming the mainstream SF_6-free solution; the ASNA atmospheric-sealed natural air technology of HM Power realises this route in practice, with no gas filling, no gauge pressure and approximately 40 years of maintenance-free operation.

A Appendix A — Glossary

- 1. SF_6 (sulfur hexafluoride): a potent greenhouse gas, formerly widely used for insulation and arc quenching in power switchgear.
- 2. GWP (global warming potential): a relative index of the warming effect of a gas, referenced to CO_2 (= 1); this paper adopts the 100-year horizon (GWP-100).
- 3. GIS: gas-insulated switchgear.
- 4. RMU: ring main unit, a compact switchgear assembly used for ring-connected distribution networks.
- 5. Vacuum interrupter: a switching element that extinguishes the arc in vacuum; it has high breaking capability and requires no maintenance, and compensates for the limited arc-quenching capability of environmentally benign gases.
- 6. g^3: Green Gas for Grid, an environmentally benign gas solution introduced by GE, now GE Vernova, in 2014, comprising approximately 5% C_4F_7N and 95% CO_2.
- 7. AirPlus: an environmentally benign gas solution introduced by ABB with 3M in 2015, in which $C_5F_{10}O$ is mixed with dry air or CO_2.
- 8. ASNA: Atmospheric sealed Natural Air, the atmospheric-sealed natural air insulation technology patented by HM Power.

B Appendix B — References

- [1] GWP-100 of SF_6 approximately 23,500 and atmospheric lifetime approximately 3,200 years (IPCC AR5). Source: IPCC Fifth Assessment Report, Working Group I (2014); for the citation convention used in China, see the methodological note of the Ministry of Ecology and Environment. https://www.mee.gov.cn/xxgk2018/xxgk/xxgk06/202510/W020251013728369855222.pdf
- [2] Regulation (EU) 2024/573, timetable for restricting the placing on the market of SF_6 switchgear: 24 kV and below from 2026, 24–52 kV from 2030, above 52 kV from 2032. Source: EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32024R0573
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- [4] Early refrigerant gases such as R12 and R134a have a relative dielectric strength of approximately 0.85–0.90 that of SF_6. Source: Comparison Between Different Gases Used as Insulation Medium in High Voltage Technology and their Effect on the Environment, which gives approximately 0.90 for R12 and approximately 0.85 for R134a; see also Electric Power Systems Research 163 (2018) 532–540, on the dielectric properties of tetrafluoroethane (R134a) mixed with N_2 and air. https://pdfs.semanticscholar.org/3fa1/3235380db8d9d1e2a8ddf4900e1a1820de87.pdf

- [5] GWP of C_4F_7N approximately 2,100, atmospheric lifetime approximately 30 years, liquefaction temperature at atmospheric pressure approximately -4.7 °C. Source: Transactions of China Electrotechnical Society, research progress on fluorocarbon environmentally benign insulating gases (in Chinese). https://dgjsxb.ces-transaction.com/fileup/HTML/2026-15-5265.htm
- [6] g^3, approximately 5% C_4F_7N and 95% CO_2, has a GWP more than 99% below that of SF_6 and operates at approximately -30 °C in high-voltage equipment. Source: GE Vernova. https://www.gevernova.com/grid-solutions/press/gepress/ge-and-hitachi-abb-power-grids-sign-landmark-agreement.htm
- [7] Relative dielectric strength of $C_5F_{10}O$ approximately 2.1, boiling point approximately 26.9 °C, GWP below 1. Source: CIGRE Science & Engineering. https://cse.cigre.org/cse-n027/application-of-sf6-alternatives-for-retro-filling-existing-equipment.html
- [8] The ABB medium-voltage SF_6-free solution uses a vacuum interrupter with dry air or nitrogen insulation, GWP = 0. Source: ABB SafeRing Air / SafePlus Air. https://www.abb.com/global/en/areas/electrification/medium-voltage/switchgear/gas-insulated/safering-safeplus
- [9] Air-insulated switchgear (AIS) accounts for approximately 40%–80% of the medium-voltage primary distribution market. Source: European Commission, assessment of F-gas substitution. https://climate.ec.europa.eu/document/download/96f3dac7-f785-4d7e-922d-aa69869b6ce4_en
- [10] Vacuum interrupters are not recognised by IEC standards as disconnecting switches, and a disconnector is normally connected in series in medium-voltage GIS. Source: CIRED 2017. https://cired.net/publications/cired2017/pdfs/CIRED2017_0614_final.pdf
- [11] HM Power technical documentation on atmospheric-sealed natural air insulation (ASNA): no gas filling, no gauge pressure, no leakage, covering 12–24 kV medium-voltage ring main units (manufacturer data). Source: HM Power website. https://www.hmpower-global.com
- [12] IEC 62271 series, high-voltage switchgear and controlgear standards.
- [13] National Development and Reform Commission, Catalogue for the Promotion of Green Technology (2020), entry on atmospheric-sealed air-insulated switchgear for SF_6-free distribution networks.
- [14] California Air Resources Board (CARB), Regulation for Reducing Sulfur Hexafluoride Emissions from Gas Insulated Switchgear, 17 CCR §§95350–95359; adopted 2010 and amended in 2021 (effective 1 January 2022) to progressively prohibit the procurement of new SF_6-containing gas-insulated equipment, phased in from 2025. Source: CARB. https://ww2.arb.ca.gov/our-work/programs/elec-tandd

C Appendix C — Further Reading

- History and origins of SF_6: HMP-WP-2601
- Greenhouse gases, GWP and control policy: HMP-WP-2602



WWW.HMPOWER-GLOBAL.COM

HM Power (Guangdong) Co., Ltd.

No.20 Xinyue Road, Shunde Science & Technology Industrial Park, Foshan City, Guangdong Province, China

sales@hmpower-global.com

Tel / Whatsapp: +86 181-3838-3310

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