TECHNICAL WHITE PAPER

HMP-WP-2501

The Evolution of RMUs and the Typical Products of Each Era

Technology generations and future directions of the RMU, seen through the evolution of medium-voltage distribution networks

ABSTRACT

The ring main unit (RMU) is the most widely distributed node-level equipment at the edge of the distribution network. Its technical evolution is not a straight line of ever more advanced insulation media, but a process advanced step by step by demand and technology: first solving "can power be supplied", then "fewer outages, easier maintenance, smaller footprint", followed by the leap to compactness and maintenance-free operation delivered by SF_6, and now compounded by greenhouse-gas constraints and the bidirectional power flow of new-type distribution networks, which impose new requirements of environmental friendliness, high reliability and circuit-breaker capability. Organised along a timeline, this paper compares five technology routes — air, oil, SF_6, solid and atmospheric sealed natural air (ASNA) — together with the parallel branches that appeared in the same periods: gas-generation type, puffer type, SF_6 load-break switch type, vacuum load-break switchgear, low-GWP fluorinated gases and pressurized dry air. For each generation it sets out the main insulation medium and the arc-quenching medium, the representative products and manufacturers, the problem solved relative to the previous generation and the price paid for it. Finally, against the changing load patterns of new-type power systems, it sets out the technical and performance requirements that future distribution networks place on RMUs. This paper provides the evolutionary background for the dedicated papers HMP-WP-2601 to 2606 and HMP-WP-2502 to 2506.

1 Introduction

The RMU is the "last kilometre" node equipment of the distribution network. At the end nodes formed by city blocks, industrial parks and residential estates, it performs ring-network interconnection, load transfer, and line and transformer protection. The technical history of the RMU is not a history of progressively more advanced media, but a process continually driven forward by demand and by technology.

The first stage solved "can power be supplied": an isolator plus a fuse carried power to the end of the feeder, with no requirement for load breaking. As load density rose, "one line fault, whole feeder out" became unacceptable and ring supply became the mainstream, so equipment had to break and make on load, isolate the faulted section quickly and transfer the healthy section. Only then did medium selection start to matter: higher dielectric strength to reduce size, and stronger arc-quenching capability to withstand load operations.

SF_6 completed the leap in the third stage: its dielectric strength is about 2.5 times that of air and its arc-quenching capability far exceeds air and oil, so a single medium pushed both insulation and arc quenching to the limit and the RMU achieved compactness, full sealing and low maintenance. The fourth stage was triggered by environmental constraints, with GWP becoming an entry criterion that operation and maintenance can no longer offset. The fifth stage faces new-type distribution networks, whose bidirectional power flow requires the equipment to clear faults locally — a requirement already beyond the boundary of a load-break switch.

Taking the timeline as its main thread, this paper analyses the key information of each period in RMU development: which main insulation medium and arc-quenching medium were used, which products and manufacturers represented the period, which problem of the previous generation was solved, and what was given up in return. Mainstream routes and the parallel branches of the same period are compared within one framework, in order to establish what actually happened along each technology route.

The scope is limited to RMUs and switchgear for 12–24 kV medium-voltage distribution networks; high-voltage GIS, low-voltage assemblies and protection devices are not covered. Judgements about specific products rest on public sources and accepted industry descriptions, with the sources listed in Appendix B.

2 From Overhead Distribution to Ring-Network Supply

2.1 Early distribution: direct overhead supply

From the end of the nineteenth century to the middle of the twentieth, distribution networks worldwide were built mainly on overhead lines. Substations fed blocks and customers directly through overhead lines, and the equipment on the distribution side was extremely simple: isolators for isolation during maintenance, fuses for overcurrent protection, and a small number of pole-mounted switches for branch control. The network was radial — a feeder ran out from the substation and a fault anywhere could interrupt the entire feeder; the equipment had no load-breaking capability, so load operations required a planned outage first. Figure 1 is a site photograph from a 1931 Swedish power journal: the wooden pole carries a pole-mounted transformer together with simple isolators, the typical form of this generation of distribution equipment — no switching, no coordinated protection, with the transformer and the fuse carrying every function.



Figure 1 — Overhead distribution in the 1930s: pole-mounted transformer and simple isolators

2.2 Formation of the ring-network concept

Once load density rose, the drawback of "one line fault, whole feeder out" could no longer be accepted. The engineering answer was the ring: several distribution nodes were connected into a loop by cable or overhead line, normally supplied from one source, with the faulted section isolated on failure and the healthy section back-fed from the second source. The outage area thus shrank from a whole feeder to one section of line, and the outage time from "repair and restore" to "switch and transfer".

This change imposed two new requirements on equipment: the node switch had to operate on load, because ring power flow has to be made and broken; and the tie point had to be permanently reliable, because it stands normally open and live, and acts only when a transfer is initiated. The load-break switch thus became the core component of ring equipment, and the engineering need to integrate incoming, busbar, outgoing and tie functions in a single enclosure was the direct motive for the birth of the RMU.

2.3 From outdoor to indoor: birth of the RMU

The earliest form of ring supply placed load-break switches and fuses on outdoor poles or in ground-level enclosures. Such equipment was inexpensive and simple, but its weaknesses were obvious: exposed to rain, wind and pollution, the insulation components were prone to pollution flashover; operation required climbing the pole or manual work on site, with poor safety; and as urban land became scarce and landscape requirements tightened, outdoor arrangements became increasingly difficult.

From the middle of the twentieth century, as urban distribution networks became more extensively cabled and loads concentrated further, ring equipment moved progressively indoors into metal-enclosed cubicles. Indoorisation brought three improvements: the equipment was protected from rain, wind and pollution, raising insulation reliability; operation and maintenance were performed in front of the cubicle, improving safety; and several units were integrated in one enclosure, greatly reducing the footprint. According to published industry sources, in 1978 Driescher of Germany exhibited the world's first SF_6 RMU at the Hannover industrial fair, after which numerous manufacturers brought out products of their own — a point in time generally regarded as the formal establishment of the RMU as a product category in its own right.

It should be noted that indoorisation by itself does not solve the breaking-capability problem; it solves the environmental and footprint problems. What actually gave the RMU "small size, strong breaking, maintenance-free operation" together was the SF_6 that followed. This also explains why medium substitution only began to accelerate after the indoor cubicle form had appeared.

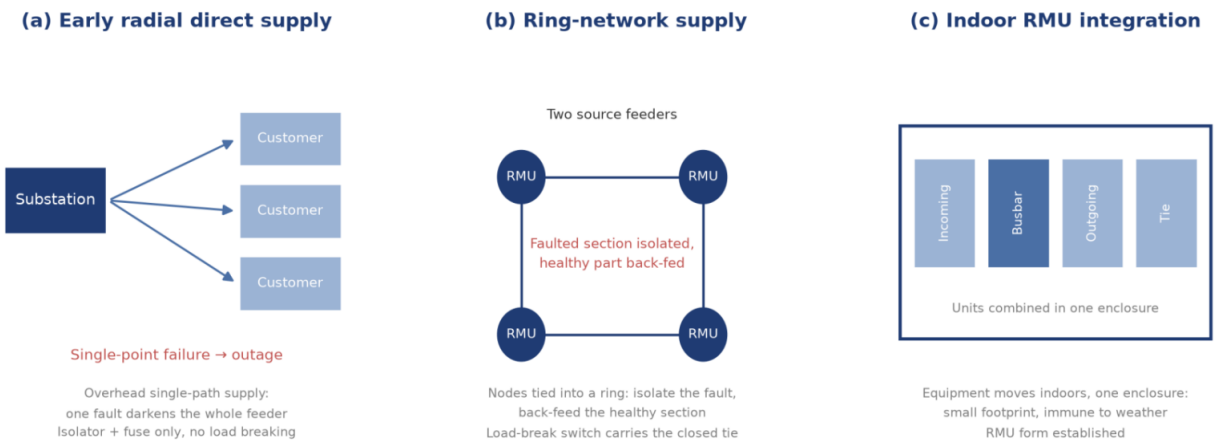


Figure 2 — Three-step evolution of distribution network form: from radial direct supply, to ring supply, to indoor cubicle integration

2.4 The evolution at a glance

Combining the process above with the technology substitutions that followed produces a complete timeline. Table 1 lists the key events and representative products of each stage, and serves as the index for the detailed treatment in Chapter 3.

Table 1 Milestones in RMU development

Time	Key event	Representative product / manufacturer
1920s–1930s	Overhead radial distribution, isolator plus fuse	Pole-mounted transformers, simple isolating devices
1930s–1950s	Ring-supply concept takes shape; load-break switch becomes the core component	AGE air-insulated load-break switch (Europe)
1940s–1970s	Oil-immersed load-break switches used in some distribution networks	UK oil-immersed load-break switch
1960s–1970s	Indoor cubicle construction appears; the RMU takes its early form	Metal-enclosed ring unit
1978	World's first SF_6 RMU	Driescher (Germany)
1985	SF_6 fully gas-insulated RMU, 24 kV	GA type (fully gas-insulated)
1990s	RMUs introduced in China, mainly gas-generation and puffer type	Domestic gas-generation / puffer type RMUs
1995	Gas-generation RMUs withdrawn from promotion (joint document of two ministries)	—
1990s–2000s	Air insulation with SF_6 quenching (semi-sealed form) becomes mainstream	SM6 series (Schneider Electric)
Around 2007	Solid insulation and environmentally friendly gas routes explored in parallel	Solid-insulated vacuum cubicle; g^3, AirPlus
2010 to date	Atmospheric sealed natural air insulation route engineered	ASNA series (HM Power)

3 Technology Evolution and Typical Products

Following the timeline, this chapter describes the technical form and construction of the RMU generation by generation, sets out how the main insulation medium and the arc-quenching medium changed, and derives the optimum solution for RMU technology over the period ahead.

3.1 The air-insulation era (1920s–1970s)

> Main insulation medium: air | Arc-quenching medium: gas-generating material / compressed air / vacuum (three types of load-break switch)

Air insulation is where the RMU began. Live conductors were exposed directly to the atmosphere, phase-to-phase and phase-to-earth insulation was provided by air, the enclosure was open or semi-enclosed and the main circuit was not sealed. Breaking capability depended on the load-break switch fitted, and three arc-quenching methods appeared in succession: the gas-generation type used a solid gas-generating material that decomposed under arc heat and blew the arc through a quenching chamber; the puffer type compressed air in a cylinder by a piston at the instant of opening and blasted it through a nozzle onto the arc, stretching and cooling it until it extinguished; and the vacuum type relied on a vacuum interrupter.
Figure 3 shows an early air-insulated three-pole load-break switch, where the contacts, insulating supports and manual operating handle are visible — it has no sealed gas chamber and its breaking capability depends entirely on contact movement and air blast, which also means it can only break load current, has a limited life, and cannot clear a short-circuit fault.

This generation was widely used in European distribution networks during the first half of the twentieth century. According to industry sources, air-insulated load-break switches represented in the early European market by AGE were simple to build and easy to maintain, and together with a fuse formed the most basic ring unit. The form has never disappeared entirely: where the substation conditions are good and cost is sensitive, the air-insulated vacuum load-break switchgear remains a realistic choice (see 3.4).

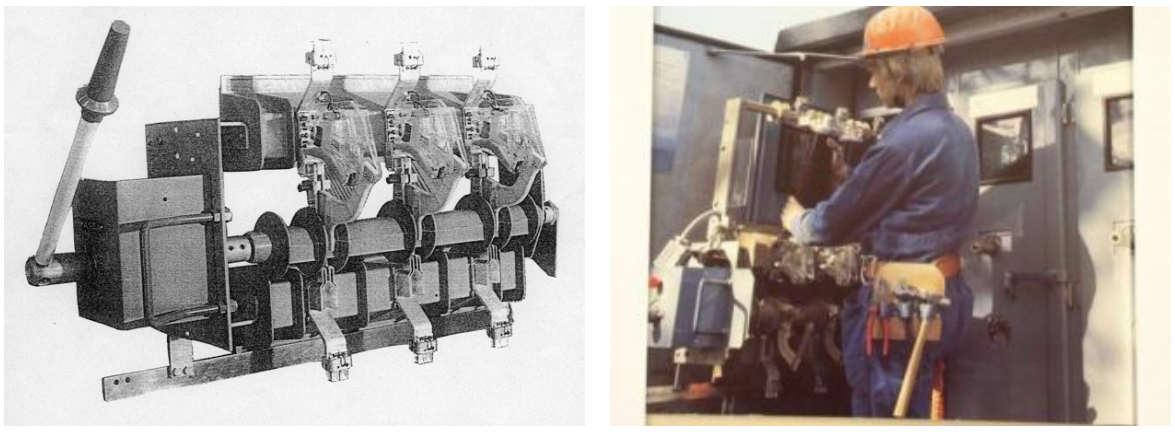


Figure 3 — Early air-insulated three-pole load-break switch: no sealed gas chamber; breaking relies on contact movement and air blast

Its advantages are clear: simple construction and low cost; air insulation recovers by itself after breakdown; and operating experience is mature, with interchangeable spares and tools. Its shortcomings are equally clear: the dielectric strength of air is only about 0.4 that of SF_6, so an equivalent insulation level requires larger clearances and the enclosure becomes bulky; the main circuit is not sealed, so moisture, dust and salt fog entering the enclosure form a polluted wet layer on insulating surfaces, causing creepage and even breakdown; regular cleaning and dehumidification are needed, which is a heavy maintenance burden; and the open construction gives weak protection against internal arcing. These four shortcomings drove the next step towards sealing and compactness.

3.2 The oil-insulation attempt (1930s–1970s)

> Main insulation medium: insulating oil | Arc-quenching medium: insulating oil (one medium for both insulation and arc quenching)

Oil insulation is a period that is easily overlooked, yet it was applied at scale. The idea was to immerse the contacts and the main circuit in insulating oil, with the oil providing insulation and arc quenching at the same time — the most complete realisation of "two media in one". According to industry sources, oil-immersed load-break switches were used fairly widely in early British distribution networks, and oil-insulated ring units were developed on that basis.



Figure 4 — Oil-immersed load-break switch

Its advantages were that the dielectric strength of oil is far higher than that of air, so the equipment could be markedly smaller; the oil also quenched the arc, giving better breaking performance than air switches of the same period; the sealed construction kept out external pollution and moisture, improving environmental adaptability; and the manufacturing process could draw on transformer practice, keeping cost under control. Before SF_6 appeared, this was the only realistic technical combination offering both compactness and strong breaking.

The price of "one oil for two duties" is that the medium itself is consumed in a single breaking operation. The high temperature of the arc decomposes the mineral oil, producing dissolved gases such as hydrogen, acetylene and methane together with free carbon and metal debris; carbon particles suspended in the oil lower the breakdown voltage, moisture ingress lowers withstand voltage further and accelerates ageing of insulation components, forming a cycle of deterioration, moisture absorption and further deterioration. Such equipment therefore requires complete oil management: periodic sampling and testing of breakdown voltage (IEC 60156), water content, dielectric dissipation factor and dissolved gas analysis (DGA), with filtration, reclamation or oil replacement according to the limits; in-service oil with a breakdown voltage below about 30 kV has to be treated, and below 20 kV it is usually replaced or fully reclaimed. The system is technically perfectly feasible, but it turns distribution equipment that ought to be maintenance-free into equipment requiring periodic outage intervention — a structural burden for a distribution network with many widely scattered, unattended points.

Beyond the maintenance burden there are two further shortcomings that are hard to eliminate: insulating oil is combustible, and an internal fault arc decomposes and gasifies the oil, raising pressure sharply and in severe cases spraying burning oil, to which dense urban areas and underground distribution rooms are especially sensitive; and the disposal of waste oil and filter elements carries environmental cost. Together these factors progressively removed oil insulation from the mainstream of medium-voltage distribution after the 1970s, leaving it only in certain assemblies and transformers.

3.3 The SF_6 era begins (1978–1990s): two design forms

Main insulation medium: SF_6 (fully insulated) / air (semi-sealed) | Arc-quenching medium: SF_6

In 1978 Driescher of Germany exhibited the world's first SF_6 RMU at the Hannover industrial fair, and SF_6 quickly became the mainstream medium for medium-voltage ring equipment. But "using SF_6" is not one solution but two quite different ones, which are often conflated in industry discussion; they differ in gas inventory, extent of sealing, cost and application.

The first is SF_6 gas full insulation, also called gas-insulated or GIS-type RMU in the industry. The entire main circuit — busbar, load-break switch or circuit-breaker contacts, earthing switch — is enclosed in a pressurized gas tank, SF_6 provides both main insulation and arc quenching, and the tank is held at a pressure that secures the dielectric strength. The GA type introduced in 1985 is representative of this form, at a voltage rating of 24 kV, with a smaller gas inventory than comparable products. Such products are the most compact and the most environmentally adaptable, but the gas inventory is large — several kilograms of SF_6 per cubicle is common — and the pressure of leakage and end-of-life recovery is concentrated here.



Figure 5 — SF_6 fully insulated RMU

The second is the SF_6 load-break switch type, the semi-sealed solution. Main insulation remains air, and only the arc-quenching and isolating contacts of the load-break switch are placed in a small SF_6 gas chamber, while the enclosure itself is unsealed. Schneider Electric's SM6 series is the typical representative of this form. Its gas inventory is typically an order of magnitude smaller than the fully insulated solution, at lower cost and with easier maintenance; the price is that the main circuit is still exposed to the air inside the enclosure, requiring degree-of-protection and dehumidification measures, and that it is larger than the fully insulated solution.



Figure 6 — Air-insulated RMU with an SF_6 load-break switch

Both forms share the core advantages of SF_6: a dielectric strength about 2.5 times that of air, so an equivalent insulation level can be achieved at a much smaller size, which fundamentally removes the bulk problem of air insulation; an arc-quenching capability far beyond air and oil, allowing load operation; and full or partial sealing, which makes the equipment essentially immune to pollution, humidity and salt fog, with no cleaning and little maintenance, in line with the move towards unattended distribution networks. These advantages made the SF_6 cubicle almost the default choice for medium-voltage distribution for more than thirty years.
Both also share the same defects, differing only in "how much is used and how much leaks": SF_6 has a GWP of 23,500 and an atmospheric lifetime of about 3,200 years and is a controlled greenhouse gas; after leakage the pressure falls and insulation and arc quenching decay accordingly, while leakage of a colourless, odourless gas is hard to notice directly; under arcing it decomposes into toxic and corrosive products such as disulphur decafluoride (S_2F_{10}) and hydrogen fluoride (HF); and its whole life requires leak detection, gas topping-up and recovery, with high medium-management cost. These five defects are the starting point of "SF_6 phase-out" (see HMP-WP-2601 and HMP-WP-2602 for detail).

3.4 Introduction and localisation in the Chinese market (1990s–2000s)

Main insulation medium: air / SF_6 (two parallel routes) | Arc-quenching medium: gas-generating material / SF_6 / vacuum

The RMU started in China in the 1990s, with early products fitted with gas-generation and puffer load-break switches. The gas-generation type was the first to be used on a large scale in China: a solid gas-generating material such as acrylic glass decomposes under the arc and the gas produced blows the arc out, giving simple construction, low cost and independence of any external gas source; but the arc-quenching capability is limited and the gas-generating material is consumed over repeated operations, so breaking performance decays with age. In August 1995 the Department of Major Equipment of the Ministry of Machine-Building Industry and the Department of Safety Supervision and Production Coordination of the former Ministry of Electric Power issued a joint document discontinuing the promotion of gas-generation RMUs. That official withdrawal was a landmark event: technology choice for distribution equipment depends not only on the performance of a single unit but on long-term operating reliability and the cost of standardised management.

Domestic products subsequently developed along three paths. The first is the SF_6 gas fully insulated RMU, which grew quickly as urban networks demanded maintenance-free, compact equipment and which dominates the installed base. The second is the SF_6 load-break switch type (such as the SM6 series), with air insulation for the main circuit and gas only in the quenching unit, balancing cost and breaking performance and widely used at small and medium load nodes.

The third is the air-insulated vacuum load-break switchgear, very common in China and comparatively rare abroad. Its main insulation is air and the enclosure is unsealed, with breaking performed by a vacuum interrupter, that is "air insulation plus vacuum quenching". According to industry sources, at the time of its introduction it cost about 30 percent less than an SF_6 load-break switch, offered excellent breaking capability, contained no greenhouse gas, and had a long electrical life and low maintenance in the vacuum interrupter, making it a cost-effective solution. Its weaknesses are a larger footprint, with the insulation inside the enclosure exposed directly to ambient humidity and pollution, requiring good substation conditions and dehumidification. It has long retained its share in China for three reasons: a mature vacuum-interrupter supply chain at low cost; higher substation construction standards making the environment controllable; and cost-sensitive small and medium projects that are not demanding on footprint. In Europe and North America, medium-voltage distribution favours fully sealed gas insulation or semi-insulation, so this form is markedly less common there.

The coexistence of three paths forms the particular picture of Chinese medium-voltage distribution: fully insulated SF_6 leads new build, the semi-sealed type covers the installed base and small to medium nodes, and vacuum air insulation holds its scale in specific scenarios. This also carries a warning: the discussion of "SF_6 phase-out" cannot be one-size-fits-all, because the object being replaced differs and so do the technology path and the cost — replacing a fully insulated cubicle means solving "insulation in a small volume", whereas replacing a semi-sealed cubicle means solving only "arc quenching".

3.5 Exploration of solid insulation and low-GWP fluorinated gases (2007–2015)

Main insulation medium: epoxy resin / fluorinated gas mixture | Arc-quenching medium: vacuum / gas

As environmental pressure on SF_6 increased, two exploratory routes appeared in the industry at the same time. Before describing them, one term has to be clarified — because both are loosely called "environmentally friendly gas", whereas in fact they are not the same class of thing.

In everyday industry usage, "environmentally friendly gas" mostly refers to mixtures of a fluorinated synthetic gas with CO_2, N_2 or air: with C_4F_7N (perfluoroisobutyronitrile) or $C_5F_{10}O$ (perfluoroketone) as the arc-quenching and insulating components, represented by g^3 (GE with 3M) and AirPlus (ABB with 3M). Their "environmental friendliness" is relative to SF_6: GWP falls from 23,500 to the range of several hundred to two thousand depending on composition and mixing ratio, but remains significantly above CO_2, is still non-zero, and the substance is still a controlled fluorinated gas whose leakage and end-of-life handling are equally subject to F-gas-type regulation. This is a different concept from the dry air and nitrogen discussed in 3.6, which are taken directly from the atmosphere, contain no fluorine and have a GWP close to zero. Calling both "environmentally friendly gas" is the most common source of misunderstanding in current technical discussion, and a grey area in much promotional wording.

The first route is solid insulation: the primary circuit is wholly cast and encapsulated in a solid material such as epoxy resin, the solid carries the main insulation, and breaking is performed by a vacuum interrupter — commonly called a "solid-insulated vacuum RMU" in China. It contains no insulating gas, so there is no leakage and no greenhouse gas. Long-term operation, however, exposed inherent difficulties: casting is hard to control, and large components readily develop voids, cavities and cracks that become partial-discharge hazards; partial discharge accumulates and develops over time, and once breakdown occurs the insulation damage is irreversible, which is fundamentally different from the self-healing behaviour of air and gas insulation; the coefficients of thermal expansion of epoxy and copper differ greatly (about $6.0–6.5\times10^{-5}$/°C for epoxy against about $1.8–2.4\times10^{-5}$/°C for copper), so long-term heating and short-circuit impact readily produce internal stress cracking; heat dissipation is difficult once encapsulated; and the solid material is hard to recycle at end of life. These factors produced quality problems after batch trials, and the procurement share has long remained low.



Figure 7 — Solid-insulated RMU

The second route is the pressurized solution using the fluorinated gas mixtures described above: the pressure-bearing structure of the SF_6 tank is retained and only the medium is changed. The strength is that the mature tank design and manufacturing system can be reused, compactness is well preserved and dielectric performance approaches that of SF_6; the weakness is that the equipment is still pressure-bearing, so the leakage risk and the need for pressure monitoring have not been removed, the medium contains fluorine with a non-zero GWP, some components have relatively high boiling points and require heating or additional pressure at low temperature, and cost is high with limited long-term operating experience (see HMP-WP-2603).

Set side by side, neither route solves the fundamental problem of medium dependence: one stakes reliability on the solid casting process, whose defects are irreversible; the other stakes reliability on pressure and a fluorinated gas, where insulation is lost as soon as pressure is lost and the fluorine content remains regulated. The way out can only be to remove both variables — pressure and fluorine — at once, which is exactly what the next route does.

3.6 Return to air insulation: two diverging routes (2010 to date)

Main insulation medium: air (atmospheric sealed / pressurized dry air) | Arc-quenching medium: vacuum

After two rounds of lessons — gas leakage and solid deterioration — the industry returned to air insulation. But "returning to air" did not become a single path; it split into two technology routes: one encloses natural air in an enclosure at atmospheric pressure, keeping internal and external pressures equal through a pressure-balancing device, which is atmospheric sealed natural air (ASNA) insulation; the other pressurizes industrially prepared dry air or nitrogen and seals it in the tank, which is pressurized dry air (or nitrogen) insulation. What they share is "air for insulation, vacuum for quenching"; what divides them is two variables: pressure and source. Both routes now have numerous applications, but their technical logic and maintenance requirements are entirely different and must not be conflated when selecting equipment.

The first is pressurized dry air insulation. Its approach is to follow the structure and process of the SF_6 tank, replace the medium with dry air or high-purity nitrogen, and maintain a positive pressure above 130 kPa inside the tank (this figure is gauge pressure; design gauge pressures differ between manufacturers and voltage levels, and 130 kPa is only an illustrative reference value), using the higher pressure to raise dielectric strength and preserve a compact size. The advantages are direct: no fluorine, a GWP close to zero, direct reuse of the mature welded stainless-steel tank and production line, fast time to market, and a size comparable to an SF_6 cubicle. But it does not remove the variable of pressure: leakage is always present, air molecules are smaller and sealing requirements are higher. Insulation falls after leakage and pressure monitoring and topping-up are still needed; and because the dielectric strength of air is low, reaching the insulation level at a limited pressure often requires higher pressure or larger clearances, raising the demands on tank manufacturing and the cost. In technical logic it is "change the medium, keep the structure" — the SF_6 pressure-bearing system is retained unchanged.



Figure 8 — Dry-air-insulated RMU

The second is atmospheric sealed natural air insulation (ASNA). Its approach is the opposite: rather than pressurizing the air, it removes the variable of pressure from the equipment altogether. The main circuit is sealed in an atmospheric-pressure enclosure fitted with a pressure-balancing device, the enclosure holds ordinary air at the same pressure as the outside atmosphere and carries no pressure; sealing and air filtration keep out dust, pollution, moisture and salt fog; electric-field optimisation, phase-separated insulation and double insulation margin compensate for the low dielectric strength of air; and a vacuum interrupter performs the breaking. These five conditions — atmospheric pressure, sealing, filtration, vacuum quenching and field optimisation — must all hold at once for the route to be valid; none can be omitted. Simply replacing SF_6 with air without changing the construction yields a conventional air-insulated cubicle in which the reasons air insulation was superseded have not been removed, only the name of the medium changed; the difference between products marketed as "air-insulated" lies precisely in whether these five conditions are met together. The left-hand side of Figure 9 shows an RMU built on this technology, and the right-hand side the actual arrangement of the vacuum interrupter inside the atmospheric-pressure enclosure — the arc-quenching duty has passed entirely to the vacuum bottle, and air provides insulation only.



Figure 9 — Left: atmospheric sealed natural air (ASNA) RMU; right: arrangement inside the atmospheric-pressure enclosure

The difference between the two routes can be summed up in one sentence: pressurized dry air trades pressure for compactness, while ASNA trades design for maintenance-free operation. The former retains the maintenance chain of the SF_6 era — pressure monitoring, periodic topping-up, seal replacement — with only the greenhouse gas changed to air; the latter cuts maintenance work down to no gauge pressure, no topping-up and no leakage, moving the cost to process precision and electric-field design at the manufacturing end. Under the real constraint of a distribution network with many widely scattered, unattended points, the latter

is worth more: it does not merely reduce emissions, it moves twenty years of operating cost forward into a single manufacturing step. For that reason, between the two air routes, ASNA is most likely to be the eventual mainstream — not because it is "greener", since both are fluorine-free, but because it removes the unreliable variable of pressure from the equipment. The pressurized dry air route will persist in specific scenarios such as high altitude, extremely footprint-sensitive sites and situations where operating habits are hard to change, but it remains in essence a pressure-bearing device whose maintenance logic has the same origin as the SF_6 cubicle.

This route was pioneered by HM Power. Development started in 2008, the first units were connected to the European grid in 2010 and to the Chinese grid in 2011, batch application began in 2013, and cumulative output now runs to tens of thousands of units with more than sixteen years of operating experience. At the end of 2020 the technology was entered in the Catalogue of Green Technology Promotion issued by China's National Development and Reform Commission as "atmospheric sealed natural air insulated cubicle technology fully replacing SF_6 in distribution networks". HM Power's ASNA (atmospheric sealed natural air) series covers 12–24 kV, achieves no gas filling, no gauge pressure and no gas leakage, occupies a footprint comparable to a pressurized-gas cubicle, and has a design life of about 40 years (see HMP-WP-2604 and HMP-WP-2605 for technical detail).

The value of this route is that it resolves the core contradictions of the preceding generations at the same time: air replaces SF_6, bringing GWP to zero and eliminating greenhouse gases and toxic decomposition products at source; atmospheric pressure replaces positive pressure, removing the risk of insulation loss through leakage and dispensing with pressure monitoring and gas topping-up; sealing replaces openness, solving pollution and moisture ingress; vacuum quenching secures breaking reliability; and electric-field optimisation offsets the low dielectric strength of air. The four costs — volume, cost, process and design capability — are transferred to the manufacturing end, borne by structural design and process precision rather than left to the operating end.

3.7 The main line of evolution and the pattern behind it

Placing all these routes on a single timeline reveals the true relation between mainstream and branches: air insulation started in the 1920s and has persisted throughout; oil insulation filled the gap briefly from the 1930s; SF_6 has dominated for thirty years from 1978; solid insulation and low-GWP fluorinated gases were explored in parallel around 2007; and after 2010 air insulation has returned in two modern routes — pressurized dry air and atmospheric sealed natural air — each extending in its own direction, the former still within a pressure-bearing system, the latter having left the pressure system altogether. The branches — gas-generation, puffer type and vacuum load-break switchgear — each occupied a stretch of application space in the gaps between mainstream substitutions.

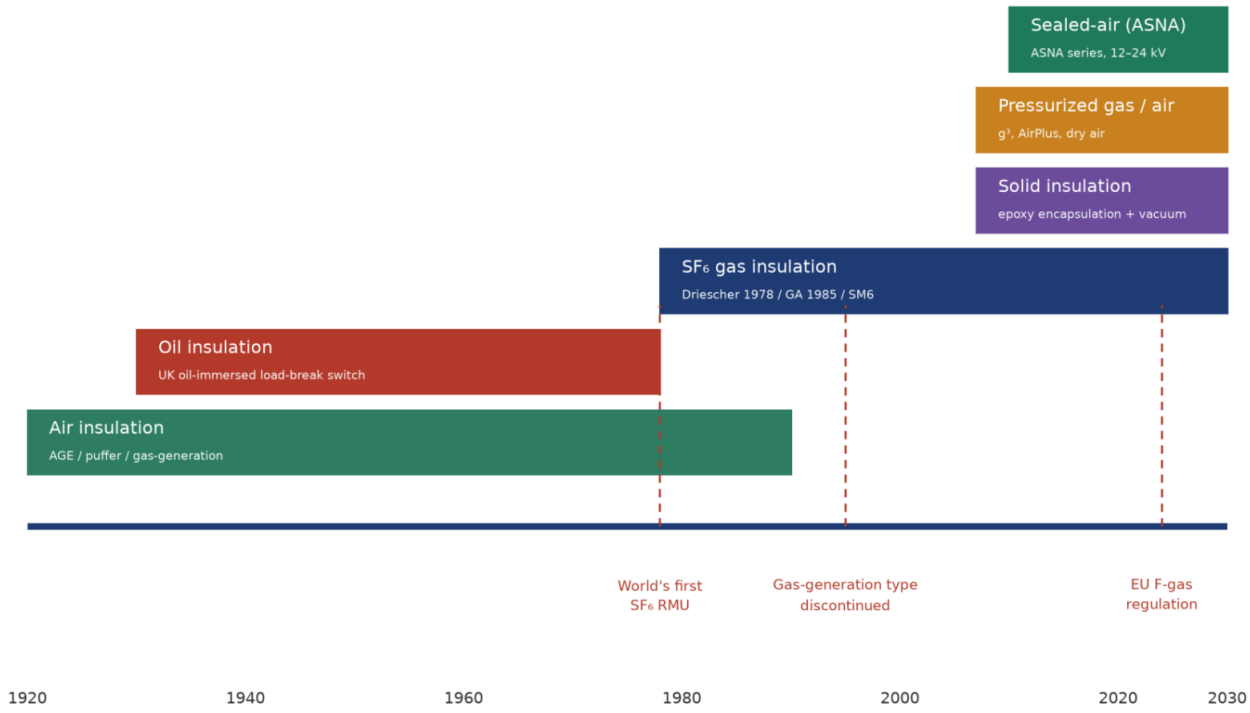


Figure 10 — Phase distribution and key milestones of RMU technology routes (band width indicates the main active period of each route)

Three patterns can be abstracted from this thread, and together they explain why technology substitution follows a spiral rather than a straight line.

First, evolution is the step-by-step solution of a ladder of demands, not the spontaneous progress of media. "Can power be supplied" comes first, then "can outages be avoided", then "can it be smaller and less burdensome", and only then "is it environmentally sound". The medium is merely the means of solving the problem; until demand has reached that step, even a far more advanced medium cannot open the market — which is why SF_6 appeared in 1978 yet was only applied at scale in China in the 1990s.

Second, every generational change redistributes among four constraints — breaking capability, reliability, compactness and environmental performance — and their priority shifts with external conditions. The air era traded volume for simplicity; the oil era traded maintenance for breaking capability; the SF_6 era traded environmental performance for compactness and maintenance-free operation; atmospheric sealed natural air trades manufacturing cost and design capability back for environmental performance while keeping compactness and maintenance-free operation. Notably, divergences within one medium obey the same logic: pressurized dry air and atmospheric sealed natural air both insulate with air, the former trading pressure for compactness and the latter trading design for maintenance-free operation — the same medium, different trade-offs, and therefore entirely different product forms and operating consequences.

Third, the mature application of vacuum arc quenching is decisive. Only because vacuum has taken over the quenching duty can the combination of "air insulation plus vacuum quenching" stand up in performance; the atmospheric sealed natural air route necessarily adopts a vacuum interrupter, not because vacuum is "more advanced", but because air can then concentrate on insulation alone. Conversely, the vacuum interrupter is the technical base that makes SF_6 alternatives viable at all — without it, no "low dielectric strength medium" route could solve the breaking problem. Once vacuum quenching is adopted, competition no longer takes place in the main insulation medium but in the structure: whether the equipment bears pressure becomes the dividing line between the air routes.

Table 2 Comparison of main technology routes and representative products

Technology route	Main insulation / arc-quenching medium	Representative products and manufacturers	Advantages	Limitations and outcome
Air insulation (open)	Air / gas-generating, puffer, vacuum	AGE air-insulated load-break switch; puffer-type and gas-generation RMUs	Simple construction, low cost, environmentally benign medium, mature experience	Bulky, sensitive to pollution, needs cleaning; gas-generation type withdrawn in 1995
Oil insulation	Insulating oil / insulating oil	UK oil-immersed load-break switch and oil-insulated ring units	Good insulation, relatively small size, low cost	Leakage, fire risk, heavy oil management; progressively withdrawn from the mainstream
SF_6 fully insulated	SF_6 / SF_6	Driescher first unit (1978); GA type (1985)	Excellent insulation and quenching, compact, fully sealed and highly reliable	Leakage risk, insulation falls after leakage, contains fluorine, GWP ≈ 23,500
SF_6 load-break switch type	Air / SF_6	SM6 series (Schneider Electric)	Small gas inventory (about 1/10 of the fully insulated type), low cost	Main circuit still affected by the environment inside the enclosure; relatively bulky
Air insulation + vacuum quenching	Air / vacuum	Domestic vacuum load-break switch RMUs	No greenhouse gas, maintenance-free interrupter, cost about 30 percent lower	Larger footprint; insulation inside the enclosure affected by humidity and pollution
Solid insulation	Epoxy resin / vacuum	Solid-insulated vacuum RMUs (several manufacturers in China and abroad)	No gas, compact, high dielectric strength	Irreversible partial discharge, thermal-stress cracking, difficult heat dissipation and recycling

Technology route	Main insulation / arc-quenching medium	Representative products and manufacturers	Advantages	Limitations and outcome
Low-GWP fluorinated gas	Fluorinated gas mixture / gas or puffer	g^3 (GE with 3M), AirPlus (ABB with 3M)	Reuses the gas-tank system, compact, GWP substantially reduced	Still fluorinated with non-zero GWP, pressure-bearing, low-temperature heating needed, high cost
Pressurized dry air / nitrogen	Pressurized dry air, N_2 / vacuum or puffer	Dry-air-insulated cubicles from several domestic manufacturers	Fluorine-free, GWP ≈ 0, reuses gas-tank process, compact	Still pressure-bearing; needs pressure monitoring and topping-up; seal ageing means leakage
Atmospheric sealed natural air	Atmospheric sealed natural air / vacuum	ASNA series (HM Power, 12–24 kV)	GWP=0, no gauge pressure and no leakage, maintenance-free, 40-year life, favourable first cost and whole-life cost	Requires all five technical preconditions to hold at once; higher demands on process precision and field design

4 Requirements and Future Directions for New-Type Power Systems

4.1 Changing load patterns

The load that distribution networks will carry over the next decade differs markedly from that of the past thirty years. First, AI data centres have become the most concentrated new load: power density per rack keeps rising, the traditional low-voltage AC supply architecture is approaching its limits in efficiency, footprint and scalability, and 800 V DC is regarded as an important direction of evolution. Second, high-power fast charging for electric vehicles brings short-term high-load impact and a relatively high harmonic content. Third, distributed PV, wind and electrochemical storage are being connected in large quantities, turning power flow from unidirectional into bidirectional, with back-feed and fault-current characteristics changing accordingly. Fourth, industrial parks, islands and remote areas are seeing microgrids capable of islanded operation, which require fast switching between grid-connected and islanded modes and adaptive protection strategies.

What these changes share is higher power density, more violent fluctuation, more variable power-flow direction and greater sensitivity to supply continuity. For switching equipment they have three underlying effects: fault currents no longer flow in a single direction, so protection set for unidirectional power flow may misjudge; the speed of restoration after a fault becomes a key indicator, and manual attendance can no longer meet it; and as the number and density of devices rise, maintenance manpower cannot grow in proportion.

The requirements that future distribution networks place on switching equipment can therefore be grouped into four items, which determine equipment form more than "which insulation medium is used".

First, faults must be cleared locally. If the equipment at a ring node is only a load-break switch, a short circuit can only wait for the upstream substation protection to operate or for personnel to arrive and isolate it, and both the fault extent and the outage time are magnified. To shorten this to "millisecond isolation, second-level transfer", the node equipment must have circuit-breaker capability and local protection logic — this is the fundamental reason for the growing demand for circuit-breaker RMUs, not a simple "configuration upgrade".

Second, whole-life cost must be predictable. The bulk of the cost of distribution equipment is not the purchase price but twenty years of inspection, maintenance, switching and replacement. If equipment requires periodic gas topping-up, oil changes or cleaning, its whole-life cost is amplified as labour costs rise. "Maintenance-free, long-life" is therefore not a slogan but a hard indicator in the cost model.

Third, operation and maintenance should be "imperceptible". Ideally, operating staff should not have to watch pressure gauges in real time, schedule outages for gas topping-up, or replace media periodically. This requires equipment with no variable that needs continuous monitoring — atmospheric pressure, no gas chamber and no oil are re-evaluated precisely from this angle.

Fourth, low carbon must cover the whole supply chain. Zero greenhouse-gas emission from the equipment itself is only the first step; energy consumption and material carbon footprint in production, losses in operation, and material recovery and disposal at end of life must all be counted. A product with GWP=0 in itself but energy-intensive manufacturing and hard-to-recycle end of life is not "greener" than an SF_6 product under carbon footprint accounting.

4.2 Technical and performance requirements for the RMU

Translating these requirements to the equipment level produces the capability list in Table 3. Compared with the technical specifications of earlier generations, it adds "local protection" and "whole-life low carbon", two items that were not on the selection list before.

Table 3 Capability requirements for RMUs in new scenarios

Application scenario	Load characteristics	Core requirements for the RMU
AI data centre	High power density, DC-oriented, zero tolerance of power loss	Supply continuity (no interruption), power density, fast protection
EV fast charging	Short-term high-load impact, high harmonic content	Strong breaking capability, short-time withstand and thermal stability, bidirectional protection
Distributed generation and storage	Bidirectional power flow, frequent switching	Bidirectional metering and protection, fast isolation, communication and dispatch interface
Microgrid and source-grid-load-storage	Islanded/grid-connected switching, variable fault characteristics	Fast switching, adaptive protection strategy, remote controllability
Dense urban areas, humid coastal sites	Limited space, salt fog and condensation	Compactness, wide environmental adaptability, maintenance-free, low noise
Industrial parks and global projects	Large maintenance radius, high labour cost	Long life, no gas topping-up or medium replacement, traceable low carbon

Taken together, future RMUs must satisfy five capabilities at the same time: zero greenhouse gas (GWP=0), maintenance-free long life, wide environmental adaptability, compactness, and intelligence (observable, communicable and self-healing). There are also two preconditions: circuit-breaker-level local fault clearing, and accountable whole-life low-carbon performance. Comparing the three existing technology routes against this set of requirements shows the differences at a glance (Figure 11).

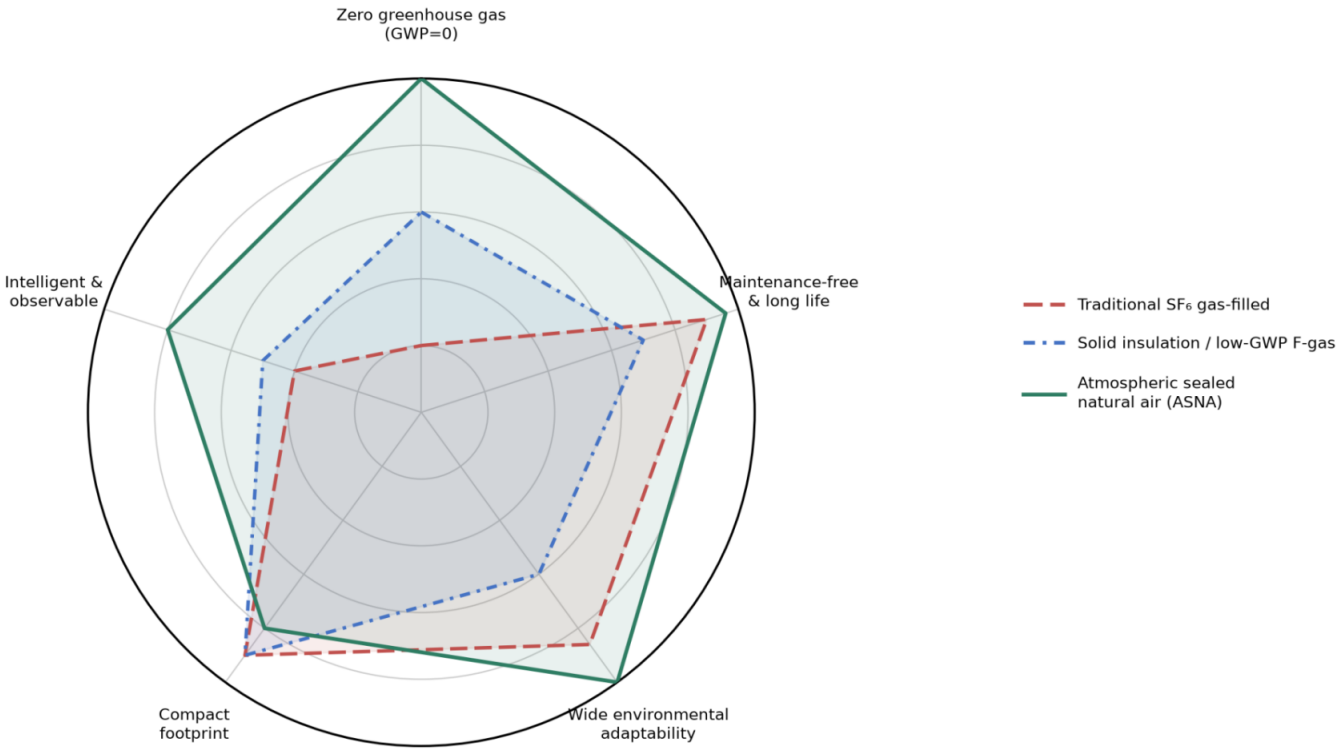


Figure 11 — Match of three technology routes against the five capability requirements (scores are qualitative; 5 = best match)

Note: this radar chart is a qualitative comparison, not a quantitative laboratory result; it is intended only to convey the concept behind each technology route.

4.3 Judgement on future directions

Based on the requirement analysis above, three judgements are offered for the coming decade (these are trend assessments, not deterministic conclusions).

First, atmospheric sealed natural air insulation will become the mainstream option for new medium-voltage distribution projects. The phased implementation of the EU F-gas regulation and the domestic green procurement orientation give the GWP=0, leak-free, maintenance-free route both policy compliance and whole-life cost advantage; products with more than ten years of operating experience will benefit first. It should be stressed that this judgement applies only to products in which all five technical preconditions hold simultaneously, not to every product labelled "air-insulated".

Second, the pressurized environmentally friendly gas route will coexist over the long term in high-voltage, extremely footprint-sensitive and special-condition scenarios, but will find it hard to return to the mainstream of medium-voltage distribution. Its fluorinated nature, pressure-bearing structure and low-temperature heating requirement constitute inherent shortcomings that are hard to eliminate entirely; solid insulation, once partial-discharge control and recyclability have substantially improved, will retain specific niche markets.

Third, the focus of competition will shift from "insulation medium" to "protection capability and scenario adaptation". Primary-secondary integration, edge computing, distributed self-healing and condition sensing will become the keys to differentiation; the medium contest at the hardware level is converging, replaced by three questions: does this node need a circuit breaker, can a fault be cleared locally, and can data be uploaded. For medium-voltage distribution equipment, whatever happens on the load side, the three basic functions of source selection, ring transfer and fault isolation are always carried by switching equipment and will not migrate because load patterns change.

5 Conclusion

A hundred years of RMU evolution can be condensed into three problem-solving steps: the first solved "is there power", carrying electricity to the end of the feeder with isolators and fuses; the second solved "does the power stay on", limiting a fault to one section of line with ring connection and load-break switches; the third solved "is it small, is it trouble-free, is it green", buying compactness and maintenance-free operation with SF_6 and then, under greenhouse-gas constraints, keeping both environmental performance and maintenance-free operation with atmospheric sealed natural air. The fourth step has already begun: new-type distribution networks require equipment that clears faults locally, adapts bidirectionally and is low-carbon over the whole life cycle — pointing to circuit-breaker RMUs and a more thorough substitution of media.

Two lessons from this thread matter more than the parameters of any single product. First, technical superiority holds only under a particular combination of constraints: SF_6 was the optimum in the 1990s and has become a burden today, and what changed is not the physical performance of SF_6 but the constraints. Second, real progress comes from structural resolution rather than point substitution: atmospheric sealed natural air represents the direction not because of the form of "returning to air", but because it uses the combination of sealing, atmospheric pressure, vacuum quenching and electric-field optimisation to resolve, in one piece of equipment, contradictions that the previous four generations could not resolve together; conversely, changing only the medium without changing the structure leaves the same old problem under a new name.

The main points of this white paper can be summarised in the following five statements:

1. The RMU was born from the need for supply reliability; in 1978 Driescher of Germany exhibited the world's first SF_6 RMU, marking its establishment as a product category in its own right.

2. Technical evolution unfolds along the demand ladder of "availability — usability — compactness and maintenance-free operation — environmental performance — intelligence"; the medium is the result driven by demand, not the cause.

3. Mainstream routes divide by main insulation medium into five: air, oil, SF_6, solid and atmospheric sealed natural air; gas-generation, puffer type, SF_6 load-break switch type and vacuum load-break switchgear, together with low-GWP fluorinated gases and pressurized dry air, form the parallel branches of the same periods, each succeeding or failing for different reasons.

4. Every generation pays with a redistribution of four constraints — breaking capability, reliability, compactness and environmental performance; the decoupling achieved by vacuum quenching is what makes low-dielectric-strength media technically viable, and is the technical base of every SF_6-free solution.

5. For new-type power systems, the RMU must satisfy five capabilities at once — zero greenhouse gas, maintenance-free long life, wide environmental adaptability, compactness and intelligence — together with two preconditions: local fault clearing and whole-life low carbon. Atmospheric sealed natural air plus vacuum quenching plus intelligent control is, at present, the realistically feasible combination for new projects in scenarios sensitive to long-term operating cost.

A Appendix A — Glossary

- Ring-network supply: a network structure in which several distribution nodes are connected into a loop, normally supplied from one source, with the faulted section isolated and the remaining section transferred to the second source on failure.
- Ring main unit (RMU): medium-voltage switchgear, usually 12–24 kV, that integrates incoming, busbar, outgoing and tie functions in a metal-enclosed cubicle.
- Load-break switch: switching device capable of making and breaking load current, with limited short-circuit breaking capability, usually used in combination with a fuse.
- Circuit breaker: switching device capable of breaking normal load current and short-circuit fault current; with protective relaying it provides local fault clearing.
- Gas-generation / puffer type load-break switch: switch that quenches the arc respectively by gas produced from decomposition of a solid gas-generating material, or by compressed air blasted through a nozzle.
- Vacuum interrupter: sealed arc-quenching element in which the arc is extinguished in vacuum, decoupling the insulation function from the arc-quenching function.
- Three-position mechanism: operating mechanism combining the closed, open and earthed positions in one unit.
- SF_6: sulphur hexafluoride, a potent greenhouse gas with a GWP of about 23,500 and an atmospheric lifetime of about 3,200 years.
- Atmospheric sealed natural air insulation (ASNA): RMU technology in which the main circuit is sealed in an enclosure at the same pressure as the atmosphere, with ordinary air as the insulating medium.
- Whole-life cost: the total cost of equipment purchase, installation, operation, maintenance, overhaul and end-of-life disposal.
- Whole-supply-chain low carbon: carbon footprint accounting and reduction requirements covering raw materials, manufacturing, operation and recycling.

B Appendix B — References and Sources (with original links)

The sources for the historical facts, data and market judgements in this paper are listed below. Early historical material is compiled from public industry sources, with individual product designations given in accepted industry wording; entries without a link are supplementary references.

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- [17] Regulation (EU) 2024/573 on fluorinated greenhouse gases. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32024R0573
- [18] IEC 62271 series, switchgear standards; IEC 60156, determination of the breakdown voltage of insulating oil.

C Appendix C — Further Reading

- HMP-WP-2601 The history of SF_6 gas, past and present
- HMP-WP-2602 Why SF_6 is being banned: what a greenhouse gas is and what GWP means
- HMP-WP-2603 The road to SF_6 substitution: from gas trials to environmentally friendly switchgear
- HMP-WP-2604 Technical development and advantages of ASNA
- HMP-WP-2605 Environmental adaptability of ASNA technology
- HMP-WP-2606 Why ASNA preferentially adopts the lower-isolation arrangement
- HMP-WP-2502 Why the insulating gas in conventional GIS switchgear is always at positive pressure
- HMP-WP-2503 Where load-break switch plus fuse combination RMUs are used, and their advantages and disadvantages
- HMP-WP-2504 Technical advantages and application of circuit-breaker-class RMUs
- HMP-WP-2505 Why conventional RMUs mainly use load-break switches rather than circuit breakers
- HMP-WP-2506 Terminal transformer protection: comparison of circuit breaker plus protective relaying against fuse combination devices



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