SF_6 or vacuum?

Choosing the right MV circuit-breaker

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More than three decades of experience in developing SF_6 and vacuum circuit-breakers, accompanied by increasingly close cooperation between the participating research centers, gives ABB a strong advantage when it comes to deciding which technology is best for a given application. The pioneering role played by the company uniquely qualifies it to pursue R&D on both fronts with the goal of pushing performance levels to the limit. The sum of this research work, coupled with unrivalled knowledge of the marketplace, puts ABB in a position to offer unbiased advice and assistance to customers searching for the switchgear that best suits their needs.

Approximately 35 years ago, in the mid 1960s, two new breaker technologies, one using SF_6 gas and the other vacuum as its arc quenching medium, were introduced to the market. Research and development work on both technologies has continued unabated since then, and today it can be said that, together, they have all but replaced the older types of switchgear. There is, however, not always agreement on which criteria should be used when choosing one of these two dominant technologies. Instead of an objective selection based on real-world characteristics, the choice is very much driven by the circuit-breaker manufacturer.

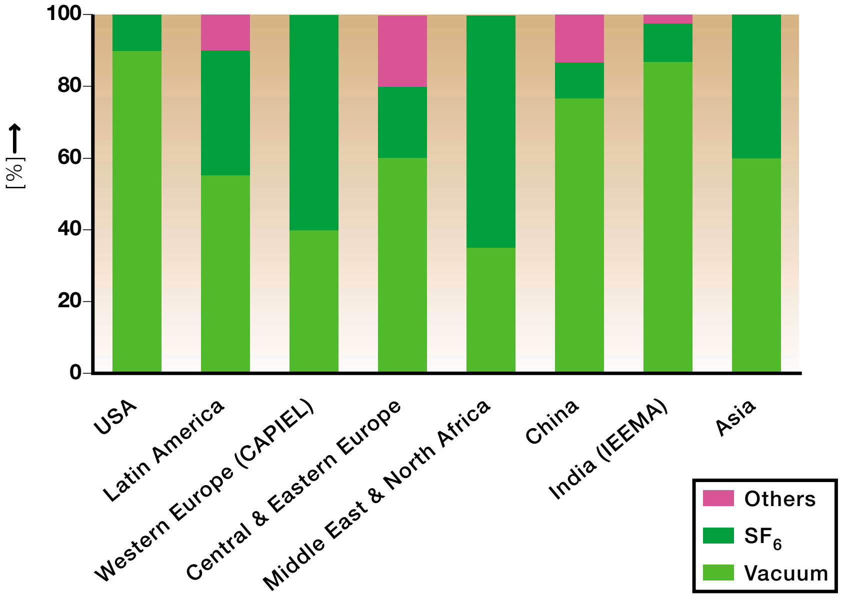
SF_6 and vacuum switchgear enjoy varying market success in the different parts of the world 1; whereas Europe and most of the Middle East countries tend to favor SF_6, China, Japan and the USA definitely prefer vacuum. In other regions, the two technologies are equally popular. Bulk-oil and minimum-oil technologies are still used in China, Eastern Europe, India and Latin America, but trends clearly indicate that these technologies will disappear very soon, to be replaced by SF_6 and vacuum.

As 2 shows, ABB concentrates today almost entirely on the two dominant technologies, and is equally present in the market with both SF_6 and vacuum.

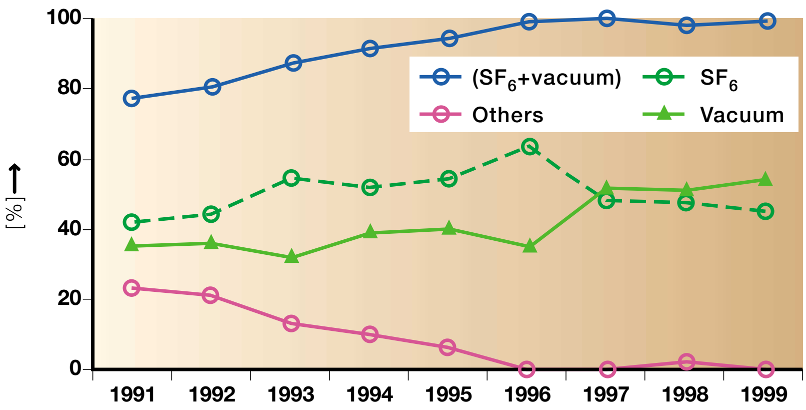
Experience with more than 300,000 MV circuit-breakers of both designs installed worldwide, backed up by over 30 years of intensive involvement in research [1], has convinced ABB that the two technologies are entirely complementary, though in some cases their different designs can be seen as alternatives. Based on this conviction that SF_6 and vacuum have equally important roles to play, the company has continued to force the development of both, and hence, as the world's largest manufacturer of MV circuit-breakers, occupies the unique position of being able to provide unprejudiced advice and assistance in the selection of switchgear for any special application.

The decision by ABB to pursue both technologies with equal emphasis has produced several important benefits. First and foremost, a profound knowledge of the behavior of the two technologies has led to better service for customers. At the same time, keen competition between the company's research laboratories has led to top team performances, the exchange of information between them having extracted the maximum synergy from parallel work. Finally, it was recognized at an early stage that it would be of great advantage to both user and manufacturer if the circuit-breakers were constructed so as to be completely interchangeable, as shown by 3.

Proceeding in this way, all new developments are equally advantageous to both technologies. The most important developments to come out of this



1 Worldwide market for MV circuit-breakers by region (1998)



2 MV circuit-breakers manufactured by ABB

approach are the use of magnetic actuators as the operating mechanism and the integration of sensors in the switchgear panels. With total interchangeability, users are faced with easier choices and structural factors are no longer a major consideration in their decisions.

Arc-interrupting characteristics

SF_6 circuit-breakers

Sulfur hexafluoride (SF_6) is an artificial inert gas with excellent insulating properties and exceptional thermal and chemical stability. These characteristics of the gas have led to its widespread use in both HV and MV switchgear, both of which exhibit very high performance and reliability as a result.

The specific advantages of SF_6 gas in electrical engineering applications have been widely recognized since the early 1930s, but it was only in the late 1950s that the first high-voltage SF_6 insulated circuit-breakers were developed and installed. SF_6 medium-voltage circuit-breakers followed some years later.

The first generation of MV SF_6 circuit-breakers employed a dual-pressure gas system. Second-generation designs included the pressure differential necessary to create the gas flow, this being provided by a mechanically driven piston which compressed a small volume of gas. The piston was integrated in the moving contact assembly. Such 'puffer-type' circuit-breakers required a relatively powerful mechanism [2]. The third generation of designs produced the gas flow by utilizing the energy contained in the arc. This 'self-blast' circuit-breaker design resulted in significantly less energy being required for its operation.

The more than 30 years of ABB experience and research associated with the puffer and self-blast circuit-breakers have now culminated in a new and very efficient design. This so-called 'auto-puffer' combines the advantages of both previous designs. The auto-puffer circuit-breaker operates as a pure puffer device when interrupting currents up to 30% of the maximum rated breaking capacity and as a self-blast interrupter at higher levels. The auto-puffer requires only a minimum amount of energy from the operating mechanism, but offers the high

3 VM1 vacuum (left) and HM1 SF_6 medium-voltage circuit-breakers with magnetic actuator

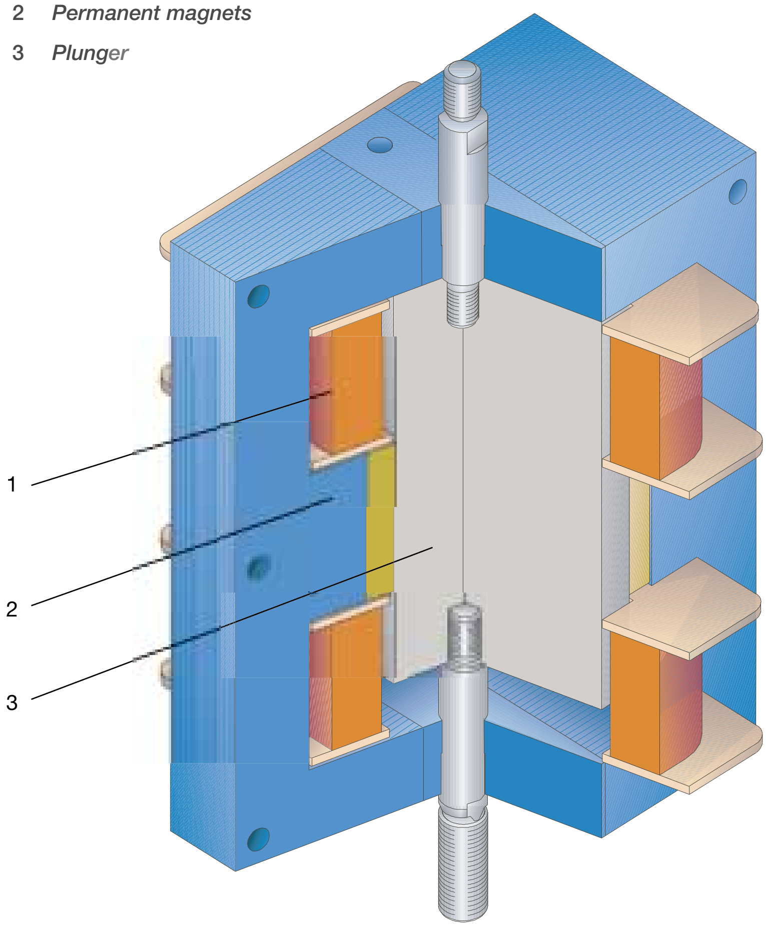
performance levels of the self-blast type. Reduced arc energy dissipation at both low and high (short-circuit) currents ensures a longer electrical life than either of the former designs. This performance is obtained without jeopardizing the total absence of chopping currents, which is a key characteristic of the self-blast technique. The design of the mechanism has been optimized to generate only enough pressure to ensure the safe interruption of currents in the range in which the puffer technique is operative. Consequently, small inductive currents are effectively interrupted with overvoltage factors lower than 2.5 pu.

4 Cutaway view of the magnetic actuator

1 *Coils*

2 *Permanent magnets*

3 *Plunger*



Vacuum circuit-breakers

As early as the beginning of the last century, the interruption of current in a vacuum was recognized as an 'ideal' switching technique. However, several practical difficulties led to it being ignored for almost three decades. One of the fundamental problems was the manufacture of a suitable insulating enclosure, which had to be hermetically sealed for life. This problem existed through a number of decades until, in the early 1960s, a solution using glass enclosures was developed. Curiously, the fundamental technology of blown-glass containers had been commonly available for centuries. A further step forward came with the development of alumina (Al_2O_3) ceramics, a material which possesses a much higher resistance to cyclic temperature stresses.

Finding a suitable material and form for the circuit-breaker contacts was also a considerable problem. The contacts had to exhibit a high resistance to arc erosion during both opening and closing operations, and any erosion had to be diffuse and even over the whole contact surface. The contact material had to have a low propensity to weld during closing as well as when closed. Low current chopping characteristics when interrupting small currents was also important, as was an adequate gettering effect. The search for a suitable material showed that chromium possessed most of the required properties. Further research showed composite material of copper/chromium to be the most suitable and best able to satisfy the basic requirements. Cu/Cr with a chromium content of between 20% and 60% is now the standard material for contacts, and is used by all manufacturers of vacuum circuit-breakers.

The mechanism of charge carrier formation gives a vacuum circuit-breaker the inherent ability to extinguish current arcs of small to medium values automatically when the current passes through zero. A satisfactory interruption of short-circuit currents, however, requires additional design measures. The initial designs used a specially shaped electrode to produce a radial magnetic field in the arc contact area. This magnetic field, reacting with the arc current, forced the arc root to move continually around the contact surface, thus preventing local overheating and uneven wear.

A further design improvement, aimed particularly at increasing the current interrupting capacity to extremely high short-circuit currents, was the development of the 'axial' magnetic field. Again a specially designed electrode is employed to generate an axial magnetic field, which distributes the arc root homogeneously over the whole of the contact area.

Common trends in SF_6 and vacuum circuit-breaker development

ABB SF_6 and vacuum circuit-breakers have been used for many years in medium-voltage switchgear and service experience has shown them to be reliable, almost maintenance-free and safe under operating conditions. Innovations in both technologies have continually improved their efficiency, reduced their overall dimensions and, most importantly, reduced the amount of energy required to operate them.

This reduction in operating energy has led to the development of an entirely new design of operating mechanism, the permanent magnet actuator.

Magnetic actuator

The operating mechanism of a circuit-breaker has the apparently 'simple' function of moving the contacts from the closed to the open position or vice versa and, when the required position is reached, of ensuring that the contacts remain in that position until a definite command to again change position is given. The operating mechanism is thus a typical bistable actuator. This function has been performed with a high degree of reliability and surety for many years by mechanical spring and latch mechanisms. However, the opportunities now offered by developments in power electronics have led to the search for a more flexible and more readily controllable operating device. Of course, an essential prerequisite of any new system was that it had to guarantee at least as good or better performance, in terms of reliability, safety and durability, than the traditional spring-based mechanism.

An appropriate solution has been found in the 'magnetic actuator'. A specially designed system combining electromagnets with permanent magnets provides the operating energy for the movement of the contacts as well as the essential bistable characteristic. The vacuum and the SF_6 interrupters are held in either their open or closed positions by the force of a permanent magnet and this without the need for any external energy. The change of status of the moving contacts is brought about by a change in direction of the magnetic field resulting from the energizing of the electromagnets, which are the control elements of the actuator. Modulation of the current supply to the electromagnets allows the energy developed by the system to be adjusted to the requirements of different types and ratings of circuit-breakers.

The resulting operating mechanism is considerably simpler in construction than the conventional mechanical system. The drastic reduction in the number of parts inherently reduces the susceptibility to failure, and the level of maintenance required by this operating mechanism is reduced to the very minimum. 4 shows the construction of such an actuator with its fixed laminated iron core, permanent magnets, steel armature and closing and opening coils. All auxiliary functions, such as interlocking, signaling, tripping, closing, etc, are provided electronically; self-diagnostic facilities are also included. An electrolytic capacitor provides the surge power required for the opening and closing coils.

Basic construction of the switching devices

The new vacuum and SF_6 magnetically actuated circuit-breakers are fully interchangeable with each other as well as with previous designs. This interchangeability is of considerable importance to plant operators as it allows existing switchgear to be re-equipped at minimum cost.

5 View of the VM1 vacuum (right) and HM1 SF_6 medium-voltage circuit-breakers showing the small number of components

4 and 5 show clearly the very small number of components used, a fact that significantly reduces the potential for failure.

Simplicity is also a feature of the embedded vacuum pole and the SF_6 interrupter using the auto-puffer technique, specially adapted for medium-voltage applications 6.

Thanks to the embedding technology there is no need for special support structures for the interrupter or its terminals.

Rapid switching

An important property of the magnetic actuator that has already been mentioned is the versatility of its control functions. Exploitation of this flexibility opens the door to new solutions to key problems in electrical distribution, problems which until today have been solvable, if at all, only at great expense. One of these issues is the rapid transfer-switching between energy sources in the event of a fault in one system. This problem has been dramatically emphasized in the last few years by an exponential increase in power-quality sensitive loads, mostly due to the use of electronic equipment. The present solution, based on power electronics devices, is very efficient from the technical point of view but also very expensive. Introduction of the magnetic actuator has made it possible to accelerate the operation of an MV circuit-breaker to the absolute minimum, that is to the pure arc extinction time. Using magnetically actuated medium-voltage circuit-breakers and appropriate basic electronics, it has been possible to reduce power source transfer-switching times to less than 40 ms. This elapsed time is so short that it solves most of the problems of sensitive loads and at a cost which is very competitive compared with the power electronics based solutions [5].

Synchronous circuit-breaker

The availability of these new circuit-breakers with their magnetic actuator mechanisms has another important advantage: they provide the basis for synchronous switching. This switching technique involves the circuit-breaker poles being independently operated, with each pole opened or closed at the best point in time relative to the current and/or voltage conditions prevailing in the relevant phase. Synchronous switching minimizes the electrical and mechanical stresses which arise on both the supply and load sides of the circuit being switched and in the circuit-breaker itself when the current is interrupted. With synchronous switching, the amount of energy which has to be dissipated in the interruption chamber is minimized and any overvoltage resulting from the switching operation is greatly reduced. All of these advantages result from the precise control of the circuit-breaker operation made possible by the magnetic actuator. The control accuracy is so great that it is possible to synchronize the completion of the moving contact travel with the current zero-crossing in each phase. Furthermore, synchronous switching minimizes, theoretically even reduces to zero, the inrush current peaks and overvoltages that occur during the energization of inductive or capacitive loads. Given the type of load, these results are obtained by controlling the closing of the contacts to correspond with either the current or voltage maximum. The closing and opening operations described are performed with a maximum tolerance of ± 0.5 ms and ± 1 ms, respectively. These figures are a true measure of the value of the technological breakthrough achieved by the combination of digital electronics with the magnetic actuator.

These developments will result in improved reliability for the entire electrical system, greater safety for the personnel, and cost reductions due to the minimization of electrical stress and wear on the electrical equipment [6].

Integration with sensors and electronics

The hardware and software presently available for use with the magnetically actuated circuit-breakers allow a further step forward in the direction of complete functional integration. With the appropriate software and the necessary current and voltage sensors, the direct integration of the protection functions in the circuit-breaker control system is now possible. This makes the circuit-breaker a fully automated device for protection and switching functions and achieves the goal of maximum reliability – the result of minimization of the component interfaces. This total integration of the core functions in switchgear has already been shown to be the correct path to follow in medium-voltage secondary distribution applications, just as it is already the current state of the art in the field of low voltage equipment.

Technical performance

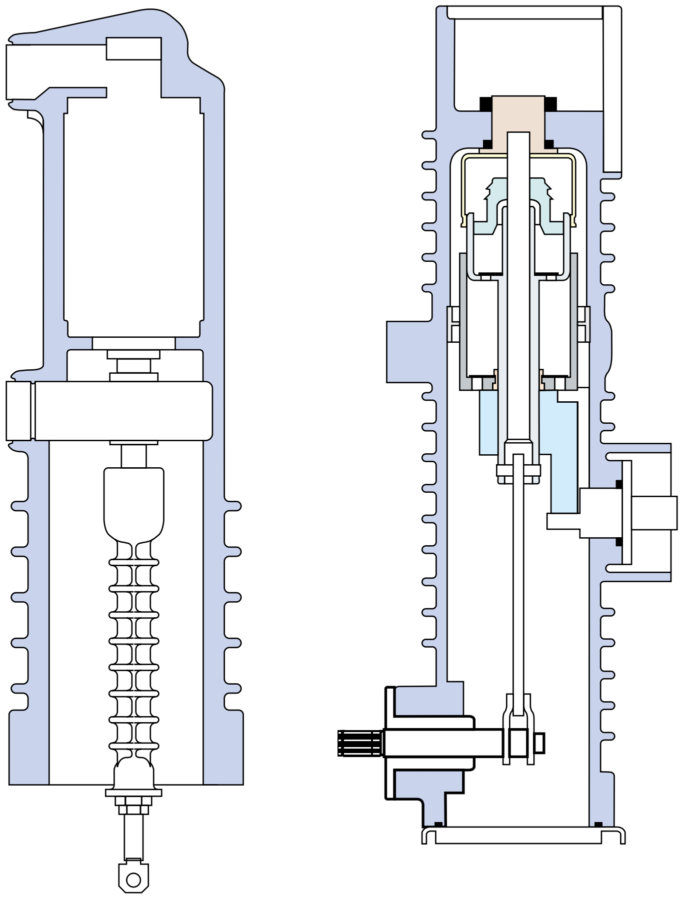
Electrical and mechanical endurance

Both SF_6 and vacuum circuit-breakers can be considered maintenance-free. High-quality SF_6 circuit-breakers as well as high-quality vacuum circuit-breakers fulfil the requirements for class B circuit-breakers as given in the IEC 60056 standard [3]. This states that:

'A circuit breaker class B (in the IEC draft document, in the future it will be E2) is a circuit breaker designed so as not to require maintenance of the interrupting parts during the expected operating life of the circuit-breaker, and only minimal maintenance of its other parts.' Based on service experience, the IEC standard establishes the number of operations that a circuit-breaker shall be capable of performing under the severe service conditions associated with an overhead line connected network and including auto-reclosing duty.

The standard prescribes two alternative test cycles for the verification of electrical endurance performance of a circuit-breaker. The test cycle in accordance with List 1 is the preferred one; the test cycle of List 2 may be applied as a valid alternative for circuit-breakers for use in solidly grounded systems. The severity level of these two test cycles is regarded as identical.

6 Section through the embedded vacuum pole (left) and the auto-puffer SF_6 pole



Reliability of dielectric media

Modern SF_6 and vacuum circuit-breakers are sealed for life; diagnostic systems for the purpose of measuring the gas pressure or the vacuum level are therefore unnecessary.

Switching overvoltages

Any switching overvoltages generated by circuit-breakers using either technology are contained within such limits as not to present any danger to connected equipment or installations.

Due to their inherently soft interruption characteristics SF_6 circuit-breakers offer this level of performance without the need of any additional devices.

Vacuum circuit-breakers using modern contact materials also exhibit low chopping currents; however, in exceptional cases, and depending on the characteristics of the individual installation, a detailed study of the system parameters may be necessary in order to determine if specific voltage limiting devices are required.

Environmental impact

The operation of either circuit-breaker type presents no health hazard to personnel. In the unlikely event of a major malfunction, overpressure valves built into the SF_6 circuit-breakers would respond, while vacuum circuit-breakers would be subject to no more than implosion phenomena. Experience has also shown that any emission products from either type of circuit-breaker do not constitute a toxic hazard. The component materials of both types of apparatus can be readily recycled at the end of their service lives. The Kyoto Protocol to the United Nations Framework Convention on Climate Change (10th December 1997) has established that emissions of six gases considered to be a likely cause of global warming, SF_6 among them, need to be reduced. It was therefore necessary to analyze the greenhouse gas (ie, SF_6 and CO_2) emissions occurring as a consequence of the manufacturing process and the power losses in service. The Life Cycle Assessment (LCA) that was subsequently carried out for vacuum and SF_6 circuit-breakers leads to the following conclusions, which are substantially the same for both types of equipment.

The impact of the manufacturing and the service phases are to be considered separately. Consideration of the SF_6 circuit-breaker shows that the environmental impact during the entire manufacturing phase is more than 100 times greater than the environmental impact of the unit throughout a 30-year total life cycle due to the fact that medium-voltage SF_6 breakers are sealed for life [4]. The production of the copper and insulating components of the circuit-breaker is the predominant contributor to the environmental impact throughout the manufacturing phase.

As regards the environmental impact during service, based on an assumed 30-year service life and an average load current of 20% of the rated current it can be calculated that the service phase has an environmental heating effect of more than 7 to 8 times that caused during the manufacturing phase. This is due to the resistance losses in the circuit-breaker. The analysis shows that the environmental impact of the SF_6 gas itself, relative to the impact of the complete apparatus over its complete life cycle, is only about 0.1% of the total. When considering vacuum circuit-breakers, it is evident that because of the quantity of copper and the number of insulating components, as well as the main circuit resistance, the results are very close to those for the SF_6 circuit-breaker.

Considering the global warming effect alone, it can be concluded that the impact is determined essentially by the main circuit power losses. However, these losses are in turn fully negligible when compared with those caused by the cables, connections and all the other apparatus which make up the electrical distribution system.

Specific switching applications

Overhead lines and cables

When applied to the onerous duty of switching and protecting overhead line distribution networks, in which the fault currents are distributed over the whole current range, both technologies provide adequate margins over and above the maximum required by the relevant standards and in normal service practice.

Transformers

Modern vacuum circuit-breakers as well as SF_6 circuit-breakers are suitable for switching the magnetizing currents of unloaded transformers with overvoltages lower than 3.0 pu. In special cases, for instance when vacuum circuit-breakers are used for switching dry-type transformers in industrial installations, the use of surge arresters is to be recommended.

Motors

When choosing circuit-breakers for motor-switching duty, attention should be paid to the problems of overvoltages during operation. The target limit for overvoltages of less than 2.5 pu is obtainable with both technologies.Where vacuum circuit-breakers are used for switching small motors (starting currents less than 600 A), measures may be necessary to limit overvoltages due to multiple re-ignitions; however, the probability of this phenomenon arising is low.

Capacitor banks

Both technologies are suitable for restrike-free switching of capacitor banks. When capacitors must be switched back-to-back, reactors may be necessary to limit the inrush currents. The synchronous control of circuit-breakers is an effective solution to this problem. SF_6 is specifically recommended for applications with rated voltages higher than 27 kV.

Arc furnaces

Arc furnace switching is often characterized by frequent operation at high current values and short intervals. Vacuum circuit-breakers are particularly suited to these service conditions.

Shunt reactors

SF_6 circuit-breakers are suitable for switching with overvoltages generally lower than 2.5 pu. Where vacuum circuit-breakers are employed, it may be necessary under certain circumstances to take additional measures to limit overvoltages.

Railway traction

In principle, both interrupting technologies are well suited for this duty; however, in the case of low-frequency applications (eg, 16.67 Hz), vacuum circuit-breakers are to be recommended.

Matching the circuit-breaker to the task

Thirty years of experience in developing, manufacturing and marketing both SF_6 and vacuum medium-voltage circuit-breakers worldwide has yielded up ample evidence that neither of the two technologies is generally better than the other, and especially that they are complementary from the application point of view. Economical factors, user preferences, national 'traditions', competence and special switching requirements are the decision-drivers that favor one or the other technology. Typical of such special applications is the switching of dry-type transformers, small-size motors, capacitors, arc furnaces, shunt reactors and railway traction systems. The need for 'frequent switching' or 'soft switching' can be an additional element influencing the choice. In such cases, a comprehensive study of the planned installation may be needed to find the best answer. ABB has the know-how and experience necessary to provide unbiased advice and assistance to users in choosing the circuit-breaker most suitable for any particular application.

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