The circuit breaker

A showcase of industrial product development

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Over the last 100 years, electricity has become the world's most flexible and reliable form of power. Global demand is increasing and, in many countries, the supply of electricity is directly linked to gross domestic product.

The infrastructure that enables the safe distribution of electrical power is extremely reliable, but the development of ever larger networks and the introduction of new types of power generators are bringing new operational challenges. In this article, ABB Review traces the development of circuit breakers, an indispensable part of the electrical grid, highlighting the contributions made by ABB and its predecessor companies, ASEA and Brown Boveri – both pioneers in electrical power.

Circuit breakers are critical to the safe operation of an electrical grid. They are needed in electricity generators, where the full power of an entire power plant (gigawatts of electricity) must to be switched on and off, and on transmission lines in substations to direct the power flow at voltages in excess of 1500 kV. Circuit breakers are also critical components in distribution grids, where very high currents need to be managed at moderate voltage levels.

A circuit breaker, irrespective of its position in a grid has two tasks: it is responsible for the daily switching of lines during normal operation, and for the disconnection of the power supply in case of overload or short circuit. Several GVA of power can be tamed by a circuit breaker within fractions of a second.

Such is the importance of this single device that tens of billions of dollars have been spent on its development over the last 100 years.[1)]

The challenge of a circuit breaker

Electrical current is transported from power plants to customers through electrically conducting, metal lines, most visible as overhead power lines. The current can be interrupted, simply by cutting the conducting power line: easy to do when there is no current flowing, but extremely difficult when the wire is live. As a live cable is being cut, the current is forced to flow through a progressively smaller cross-section of the wire. This concentration

Footnote

[1)] Circuit breaker systems in which free arcs do not form, ie, power semiconductor devices, perform extremely well at low power levels, but require further development for broader application in power circuit breakers.

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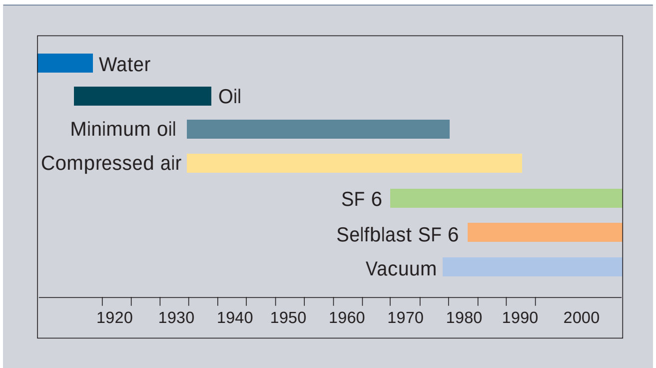
of the current leads to heating and eventual evaporation of the remaining wire. But even when the wire has been completely severed, current can continue to flow through an electrical arc that forms from ionized gases (plasma) between the opened contacts. The current can then be interrupted only by a circuit breaker capable of extinguishing this arc. While the speed with which circuit breakers must disconnect heavy metal contacts to effect their purpose has provoked a number of ingenious solutions, this article will concentrate on advances made in the considerable challenge of managing electrical arcs.

1 Major types of power ciruit breakers.



Electrical arcs have enormous energy: their temperature can exceed 50,000 °C and pressures up to 100 MPa can be contained within a volume of less than a liter. Over the years, circuit-breakers have incorporated a variety of different media to dissipate this energy, including water, oil, inert gases, and compressed air. The intense heat of the arc can be dispersed either by the application of a gas at high pressure, or by gas flow caused by the vaporization of the internal medium, which occurs as a result of arc formation.

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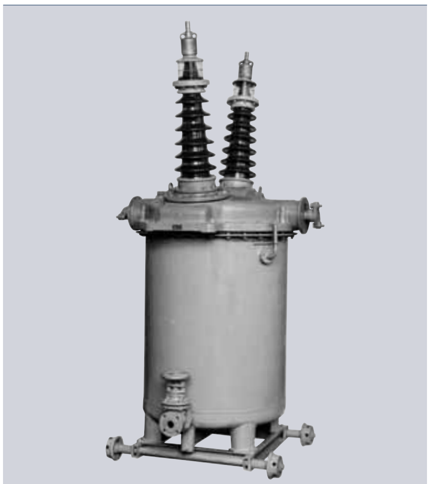
The body of the circuit breaker also plays a critical role in the effectiveness of the device. It can be used to direct the flow of hot gases, and a range of different approaches have been taken to improve heat dissipation, including the use of semi-destructible materials. 1 gives an overview of the various types of circuit breakers used over the last 100 years by ASEA and Brown Boveri, and, more recently, ABB[1)].

Water- and oil breakers appeared early on in circuit-breaker development and worked at very low levels of current and voltage. 2 shows an example of an early oil-filled circuit breaker. The contacts in these breakers were embedded in a large tank, filled with the chosen medium. Under these conditions, arc formation led to ionization of the medium and the formation of hydrogen gas. When the current approached zero (eg, every 10ms in a 50-Hz alternating system), the high pressure of the vaporized medium compressed the gas-filled arc channel. This caused the medium between the opening contacts to lose most of its conductivity, thereby quenching the arc. Unfortunately, because of the large volumes of medium they required, these devices were rather unwieldy and, if an oil breaker failed, allowing pressure to build up, there was a significant risk of explosion and fire 2. Despite these risks, oil remained a popular medium and minimum oil breakers, based on these cumbersome early devices, were used until the 1980ies. The principle underlying the minimum oil breaker is shown in 3. Briefly, when current arcs in oil, the medium vaporizes and a bubble forms around the arc. This high-pressure gas, which is almost 80 percent hydrogen, inhibits ionization and moves through the channels surrounding the arc. It enhances convection in the oil, which helps to cool the arc residuals around zero current. This arc-induced-convection principle was later used in the “self-blast” breaker.

2 Outdoor single pole oil circuit breaker from 1923, 110 kV, 350 A.



Minimum oil breakers work best on high currents that provoke a sharp rise in pressure and strong convection. At lower currents, during normal operation, the self-blast effect cannot develop fully without the help of a moving piston to encourage convection 4.

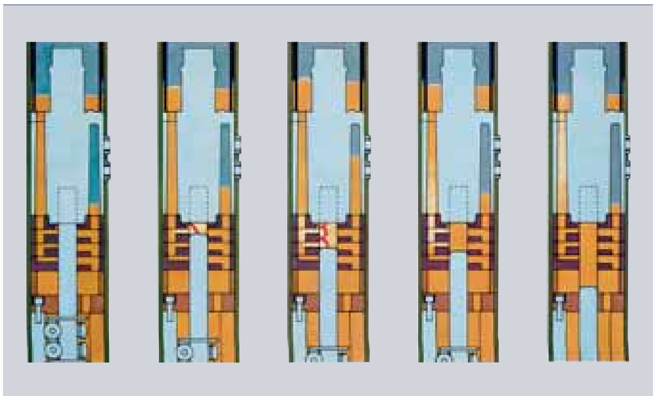
In these breakers, when the switch is opened, the current arcs and the pressure in the upper chamber rises significantly, causing the piston between the two chambers to move. At a certain point, an aperture in the piston passes the moving contact. This causes a strong axial flow of oil from the lower chamber, which cools the arc.

The obvious advantages of this approach led to a quick adoption of the minimum oil breaker and a phasing out of the conventional oil tank breaker, as the relative sales volumes around 1940 indicate 5.

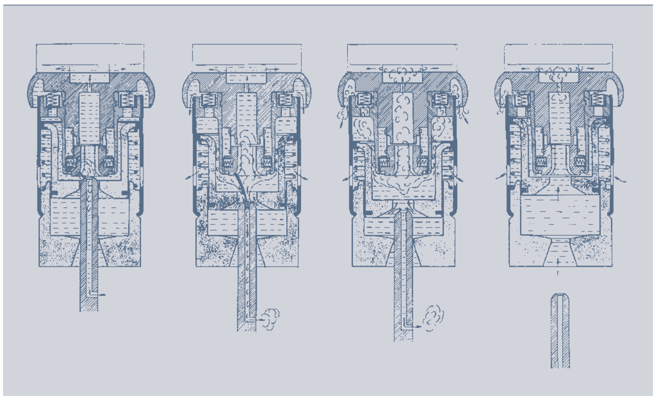
Oil is a good electrical insulator and, when the breaker is open, it can insulate grid voltage across the contacts. Comparable insulation can be achieved using air, but only if it is compressed to several MPa. The use of such high pressures in compressed-air breakers necessitated a new design of circuit breaker chamber, which was developed alongside that of the oil breakers during the early decades of electrification.

In compressed air breakers, the arc is cooled by convection caused by the large pressure differences between the inner parts of the breaker and the

3 Contact opening sequence of minimum oil breaker at short circuit current (1976).



4 The operation of the compression chamber upon breaking.



ambient air outside; a valve opens and compressed air rushes out of the chamber at high speed. A critical design component was ensuring that the arc was correctly positioned to benefit from the intense air flow. Various nozzle designs were tested and, finally, an axial flow, similar to that used in the compression chamber, was chosen.

There were several trade-offs between the compressed air breaker and the minimum oil breaker. The oil breaker, especially the self-blast type, had a simple design and could operate under low mechanical power. As a medium, however, oil was not easy to handle. It posed a fire risk and necessitated more maintenance. Compressed air breakers, on the other hand, required powerful compressors and were very noisy when operating. The high pressure could, however, be used to drive the movements of the contacts and compressed air-based systems were much cleaner and easier to maintain than their oil-based counterparts.

The market welcomed compressed air breakers and, between 1967 and 1971, sales grew by 20 percent every year. But the development of two breaker principles in parallel polarized opinion, even within the producing companies, and competition between the two camps continued with almost religious zeal. In 1955, some engineers claimed that, “The air-blast breaker is better than any other type of breaker for the high voltage level up to 380 kV”, while in 1978, others said, “The minimum oil breaker has survived the air-blast wave, which now belongs to the past, and will undoubtedly not be stifled by SF_6 [sulfur hexafluoride] either”. Market forces, however, proved both opinions wrong and the SF_6 solution is now more popular than either of its predecessors.

SF_6 is an inert gas with very good insulating properties, even at relatively low pressure (ie, 0.5 MPa). This low pressure is crucial because SF_6 would liquefy under higher pressures and be unable to interact with the arc. The principle of the SF_6 circuit breaker is shown in 6.

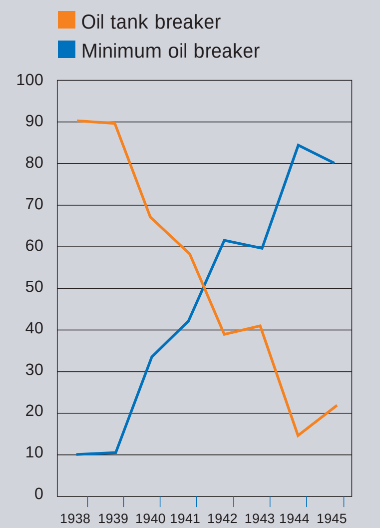
Electrical arcs have enormous energy: their temperature can exceed 50,000°C and pressures up to 100 MPa can be contained within a volume of less than a liter.

The moving contact is connected to a nozzle and a cylinder that forms the piston that compresses the SF_6 gas as the contacts move. When the arc is formed, the cold SF_6 gas, from the dynamically compressed lower part, can interact with the arc in an axial flow and diffuse its energy.

This device combines a number of beneficial features including low maintenance, clean operation, no external compression, and no exhaust noise. The use of SF_6 as a medium has proved extremely popular with customers and engineers. Since 1970, increasing investment has been made in the development of these breakers.

Capitalizing on the advantages of SF_6 as a medium, ABB engineers went on to combine it with the self-blast principle, as used in the minimum oil breaker. But the first applications of the self-blast features in an SF_6 breaker followed another path, as used in vacuum circuit breakers: using a magnetic field to control the arc. When the contacts are opened, and an arc formed, a magnetic field builds up due to the spiral form of the electrodes. This causes the arc to rotate at high speed, forcing it to mix with the cold SF_6 medium, which quickly saps its energy.

5 Sales volumne of oil breakers from ASEA around the year 1940.



Source: Asea Journal 1946, p. 17

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A few years later, the cumulated expertise in arc cooling, gas flow, material ablation and gas insulation gave rise to a lean, new SF_6-based circuit breaker. The device contained few moving parts and the contacts needed to move only a small distance before the circuit was broken. This technology was soon combined with puffer breaker features and finally led to ABB's current state-of-the-art circuit breakers, which can manage switching power of more than 25 GVA in a single chamber. This represents a 100-fold increase in performance over the last 80 years 7.

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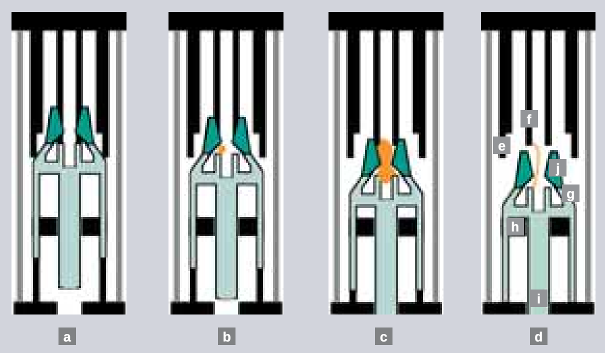
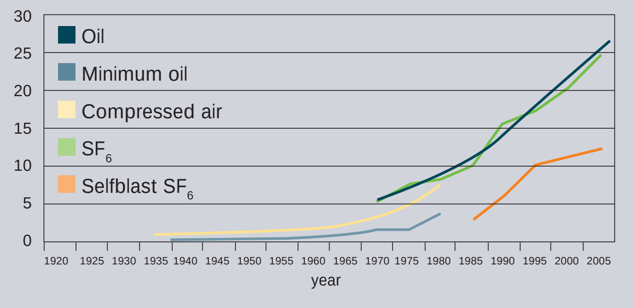
6 Operating sequence of SF_6 type breaker.



a closed position, current flows through nominal contact
b opening sequence, arc is formed between short circuit contacts
c contacts moving, piston generates high pressure, arc at maximum current
d arc close to current zero affected by forced gas flow
e contact for nominal current
f contact for short circuit current
g compression chamber
h Piston
i Hollow contact for exhaust gas
j Nozzle for ultrasonic gas flow

7 Breaker capacity per interrupter of ABB circuit breakers.



8 shows a modern Live Tank Breaker (LTB). The energy required for interrupting short-circuit current in this breaker is taken partly from the arc itself. This reduces the operational energy requirements to less than half that of a conventional SF_6 puffer-type circuit breaker. Lower energy requirements reduce stress on the breaker and therefore enhance reliability.

8 Live Tank Breaker D for voltage levels up to 170 kV and 40 kA breaking current.

All of the breaker types discussed so far rely on some kind of medium in which the electric arc develops. The vacuum circuit breaker, however, takes a different approach. When live contacts separate in a vacuum, the metal electrodes begin to evaporate and it is this metal vapor that provides a conductive medium for arc formation. Because the electrodes are spiral, a magnetic field is induced in which the arc rotates. The arc is extinguished when the metal vapor recondenses on the electrodes and walls of the breaker chamber.

Since the beginning of the 1980ies, ABB has produced well over a million vacuum interrupters. This high-tech product remains in great demand worldwide. ABB's current product range comprises vacuum interrupters for circuit-breakers from 12 to 40.5 kV, with short-circuit breaking currents up to 63 kA.

Circuit breakers of the future

The proper management of the electric arc, unavoidable in all the existing circuit breakers, has been studied and understood over the past 100 years. Of course, preventing arc formation would be preferable to managing it, if a new switching principle using power semi-conductors could be devised.

Power electronic devices are widely used in the electricity industry and high-voltage, direct-current (HVDC) systems – a major product range for ABB – are based on the best performing power semiconductors. For this technology to be applied in circuit breakers, the performance of current devices would need to be vastly improved. Current semiconductor technology would allow, at least in principle, a power circuit breaker to be designed, but it would be a highly complex, extremely costly exercise. A fully electronic breaker would not be competitive in today's market.

The history of circuit breaker development shows, however, that the combination of various established technologies in new products has been very successful. ABB is continuing that tradition and combining features of conventional breakers with power electronic devices. Further leaps in performance and development are expected in this field.

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