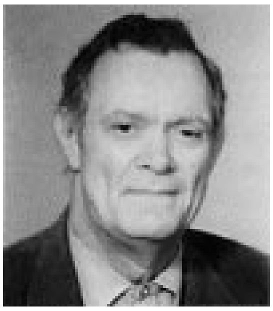

n° 171

breaking by auto-expansion

Georges Bernard

A graduate engineer from the «Institut Electrotechnique de Grenoble» (IEG), in 1960, he joined Merlin Gerin that very same year, working firstly in the Patents Department, then in the Research Departments.
In 1966 he successfully defended his PhD on optical current measurement.
Since 1961 he has been involved in SF6 breaking studies and has worked in static and hybrid breaking.
In 1993, as part of Merlin Gerin's Research and Development Management team, he carried out new breaking studies for the circuit-breakers of the future.

E/CT 171, first issued March 1995

glossary

certification organisations — the major ones are:
■ ASTA - Association of Short-circuit Testing Authority, England;
■ CESI - Centro Elettrotecnico Sperimentale Italiano, Italy;
■ ESF- Ensemble des Stations d'essais à grande puissance Françaises;
■ KEMA - Keuring Elektrotechnische Materialen Arnhem, Holland.

These organisations are international STL members (Short-circuit Testing Liaison).

electronic density — number of free electrons per volume unit ($\approx 10^{17}/cm^3$ in breaking arcs)

GIS — Gas Insulated Switchgear: hermetically closed switchgear (see IEC 298)

interferometry — very accurate measuring method based on interference phenomena (interference: phenomenon resulting from the superimposition of oscillations or waves of the same kind and of equal or similar frequencies).

MV - HV — categories of medium voltage defined by a French decree dated 14 November 1988.
Voltage levels are classified by different decrees, standards and other particular specifications such as those of utilities. AC voltages greater than 1,000 V are defined by:
■ the French decree of 14 November 1988 which defines two categories of voltage:
□ MV = 1 kV < U ≤ 50 kV,
□ HV = U > 50 kV;
■ CENELEC (European committee for electrotechnical standardisation), in a circular dated 27 July 1992, specifies:
□ MV = 1 kV < U ≤ 35 kV,
□ HV = U > 35 kV;
■ the IEC publication sets forth the highest voltage ranges for equipment:
□ range A = 1 kV < U < 52 kV,
□ range B = 52 kV ≤ U < 300 kV,
□ range C = U ≥ 300 kV.
A revision is pending, which will include only two ranges:
□ range I = 1 kV < U ≤ 245 kV,
□ range II = U ≥ 245 kV;
■ the French national utilities EDF now uses the classification given in the decree cited above.

schlieren effect — optical method revealing variations in refraction coefficients of a fluid (gas). It is used to observe temperature and pressure variations of a gas in a volume and thus to know its movements.

SF6 — sulphur hexafluoride.

vacuum — pressure less than 10^{-1} Pascal.

breaking by auto-expansion

The term «auto-expansion» is used to cover a variety of techniques or breaking methods according to technical documents and circuit-breaker manufacturers.

This «Cahier Technique» first points out the main differences concealed by this term, as regards both breaking principles and special features, and then presents breaking by auto-expansion in SF6. To date this technique is used solely by Merlin Gerin circuit-breakers.

Finally, three circuit-breaker models are presented, the performances of which are proof of the advantages of this breaking mode.

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1. history of breaking techniques

In the December 1992 issue of the Revue Générale de l'Electricité, J. CLADE, general inspector with EDF, wrote:

«For the past century electrotechnical equipment has been at the basis of development of electrical networks. In particular, substations would have taken on enormous proportions if progress, unspectacular at the time but plentiful and continuous, had not made it possible to continuously increase the specific performances of this equipment».
Control and protection switchgear, both in Low Voltage (LV) and High Voltage (HV), is no exception to this rule.

Although, in LV, magnetic air breaking, used right from the beginning, still has a future, development of breaking in MV and HV has been affected by changes in dielectric medium. In point of fact, each change in fluid made in an attempt to improve three criteria:

- performance;
- safety;
- reliability;

and to reduce costs, has resulted in a radical change in breaking technique.

Although the actual breaking technique is of little interest to users, it affects (in addition to the above criteria):

- overall cost (device - installation - operation);
- overall dimensions;
- the electrical stresses generated on breaking.

In plain language, breaking technique is decisive both technically and economically for circuit-breakers.

The history of switchgear is consequently closely bound up with that of the breaking techniques and dielectric media used.

The present situation can best be explained by reviewing the techniques used throughout the last century.

breaking techniques in MV and HV

A number of techniques, air, oil, SF6 and vacuum, are used.

Air breaking
Increased network voltage and power has led to the use of the following breaking techniques:

- auxiliary arcing contacts;
- arc blowing;
- arc elongation by magnetic effect (principle of the SOLENARC).

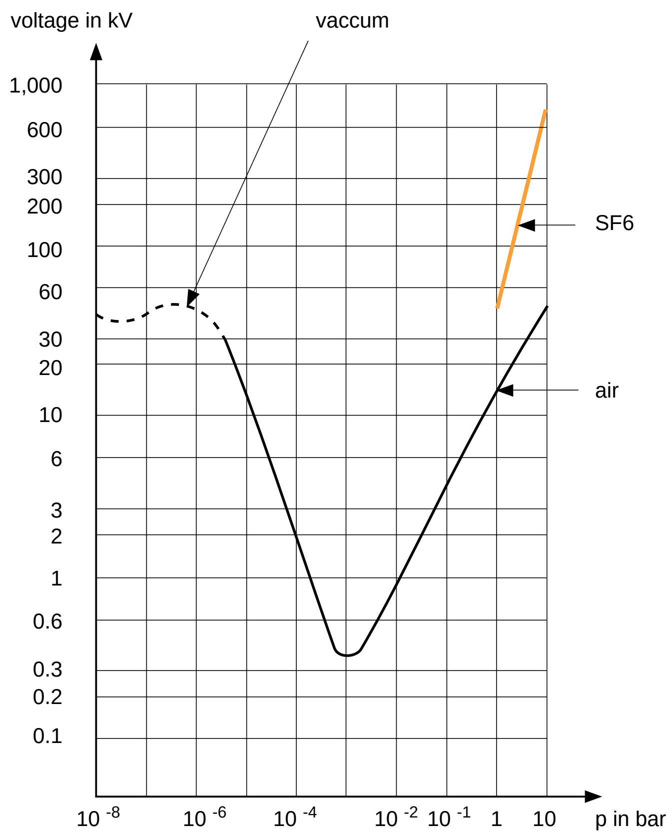


fig. 1: evolution of dielectric strength of air and SF6 as a function of pressure, in a slightly unhomogeneous field for a 12 mm inter-electrode gap.

This technique, used up to 20 kV, has virtually ceased to be used today due to the space taken up by the devices used;

■ compressed air: use of the physical properties of this dielectric (see fig. 1) has enabled important progress to be made in production of circuit-breakers for extra high voltages. However, since the switchgear using this technique is fairly complex and costly, today it is used only in high and extra high voltage in cold countries, as air has the advantage of retaining its properties at very low temperatures.

Oil breaking

This breaking mode first appeared at the turn of the century. It made possible the first HV circuit-breakers, as well as considerable reduction in overall dimensions thanks to the ROV technique (Reduced Oil Volume). These circuit-breakers are still used in the MV and HV substations of certain countries such as Brazil and the CIS (former USSR). They are currently being replaced in Europe and the USA by SF6 and vacuum circuit-breakers. Their progressive disappearance is due mainly to the dangers inherent in oil (inflammable, explosible), to the civil engineering work required to install them (retention tanks) and to the preventive maintenance involved.

SF6 and vacuum breaking

The techniques using this breaking mode, which first appeared in industry in the early sixties, are characterised by use of arc extinguishing media (SF6 and vacuum) with outstanding properties, in small, compound-filled, impervious poles, incorporating simple contacts.

SF6 and the vacuum have two advantages:

■ in transient state, a deionising time constant which can be one hundred times smaller than that of compressed air. This removes the risk of rearcing without requiring the use of contrivances such as resistors and damping capacitors;

■ in steady state, outstanding dielectric properties as shown in Paschen's curve in figure 1.

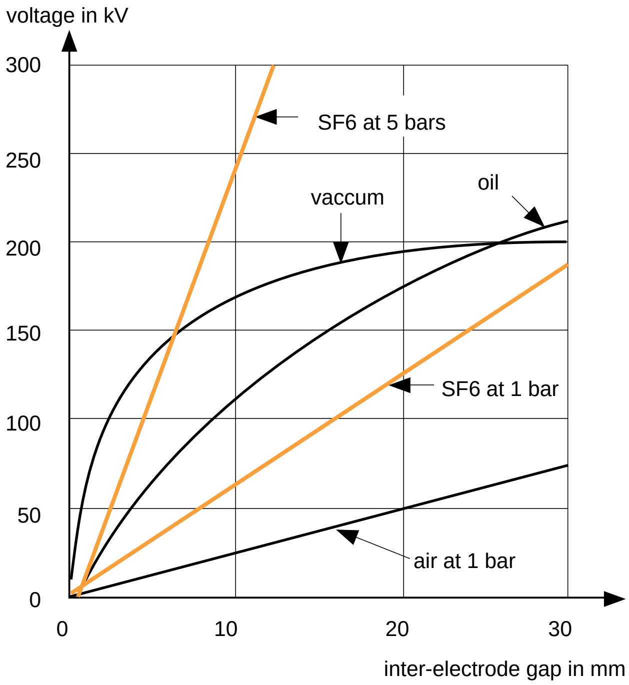


fig. 2: influence of inter-electrode gap on dielectric strength.

Evolution and field of application

In the mid-term, only SF6 and vacuum breaking should continue to exist.

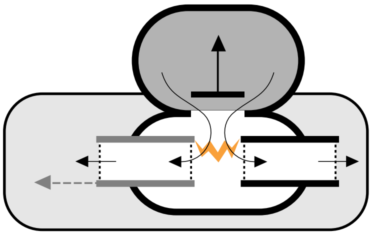
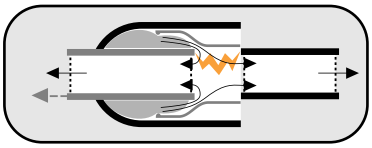
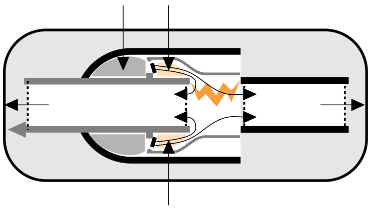
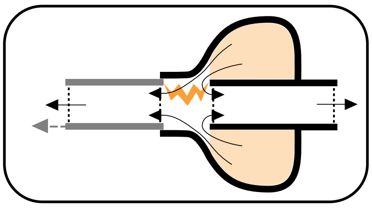
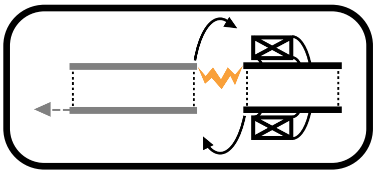
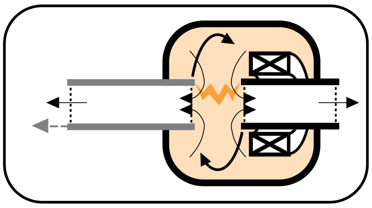
As regards fields of application, the SF6 and vacuum should share the MV market, with SF6 alone in HV (> 50 kV). Variation in dielectric withstand between electrodes (see fig. 2) shows in fact that, although the vacuum is efficient in MV, it reaches its maximum at 200 kV irrespective of inter-electrode gap.

special SF6 breaking techniques

Since the purpose of this "Cahier Technique" is to present the principle of breaking by auto-expansion, this principle must be situated among the other techniques using SF6 as a breaking fluid.

In the space of 30 years these techniques have evolved, moving progressively from arc blowing caused mechanically (double pressure, pistons) to blowing linked to the actual current (rotating arc, expansion).

These terms are used to refer to actions on the arc, separate or combined, the main aim of which is to cool the arc. They in fact vary in meaning according to the manufacturers using them. The table in figure 3, page 6, describes for each technique how the arc is blown or cooled.

diagram	terms: in this Cahier	other	description
	double pressure	pneumatic	a gas, previously compressed in a "high pressure" tank, is released on breaking by opening a valve: it blows the arc by flowing off through the tubular contacts (nozzles) to a "low pressure" tank
	puffer	auto-compression auto-pneumatic self-blowing	a gas is compressed by movement of a piston linked to contact opening. It blows the arc by flowing off through a nozzle.
	puffer and self pressure rise	auto-pneumatic and heat expansion (autopuffer-thermal blast) auto-expansion	same principle as above, but with two compression volumes: ■ a volume giving a reduced pressure for breaking small currents, hence a reduced control energy; ■ a volume "reduced" by automatic closing of valves caused by the high pressure developed by high arcing energy (heat expansion), hence reinforced blowing.
	heat expansion	self-blowing	the arc is cooled by blowing obtained by gas flowing off through the nozzle. This flow-off is due to pressure increase of thermal origin, produced by the arc around the contacts.
	rotating arc		the arc is cooled by rotation under the effect of a radial magnetic field produced by the current to be broken (Laplace's law forces).
	auto-expansion	self-blowing autopuffer self-blast	same principle as above with, in addition, arc blowing obtained by gas flowing off through the contacts. This flow-off is due to pressure increase of thermal origin produced by the arc around the contacts.

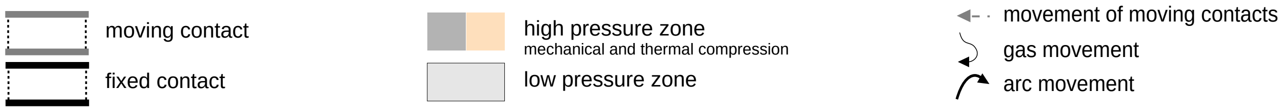


fig. 3: SF6 breaking techniques.

2. breaking by auto-expansion

auto-expansion: a new technical breakthrough

In the early eighties, in order to improve existing circuit-breaker ranges and anticipate evolution of competitors' equipment, the Merlin Gerin marketing departments drew up a list of specifications which were far more stringent than for a simple range renewal.

The company's research and design staff were thus obliged to consider a major change in the breaking techniques used. With this in mind, they set themselves the following objectives:

■ increased dependability (reliability, maintenability, availability and safety) by reducing the number of moving parts and the control energy required.

This results in:

□ overall lightening of electromechanical structures,

□ increased compactness;

■ minimisation of disturbances induced during normal operations and on fault current breaking, for the various loads:

□ motors,

□ transformers,

□ off-load lines and capacitors.

■ use of a new breaking technique, if possible the same in MV and HV to increase total experience.

In order to achieve these ambitious objectives, designers favoured a technique with no external supply source since:

■ the breaking energy (blowing energy) is taken off the actual current to be broken;

■ the breaking capacity adapts to the current to be broken;

■ the best possible use is made of the SF6's outstanding properties.

The auto-expansion technique was found to meet these specifications. Currently used in a number of circuit-breakers, it represents a new technical breakthrough in the field of breaking devices.

method

Auto-expansion combines:

■ blowing by heat expansion of the SF6;

■ arc control and blowing by electromagnetic effect.

Blowing by expansion

The arc naturally forming between the contacts when they open dissipates an energy:

$$W = \int_0^t (Ua \ i) \ dt$$

where Ua = arcing voltage.

This energy is discharged, either directly or indirectly, by:

■ conduction;

■ radiation;

■ convection.

Figure 4 illustrates this dissipation.

In auto-expansion devices, roughly a quarter of arcing energy is transmitted to the SF6 which begins to heat.

If the contacts are enclosed in an impervious volume (upstream volume, see fig. 5), the increase in temperature

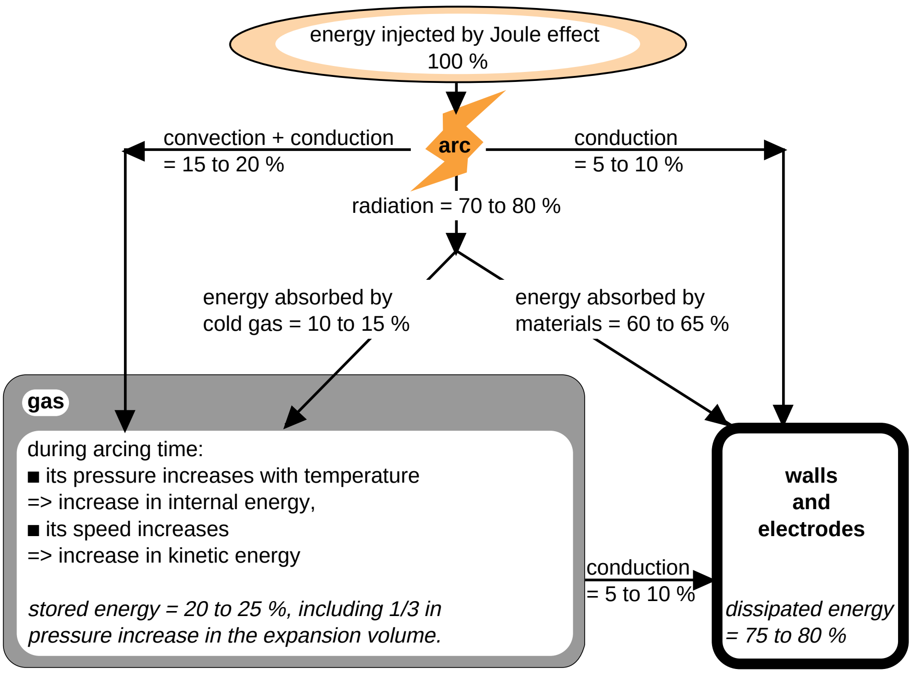


fig. 4: energy fluxes on current breaking according to modelling.

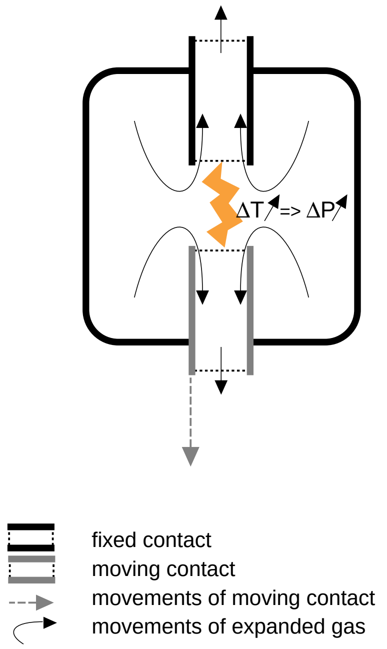


fig. 5: principle of breaking by expansion in SF6.

causes build-up in gas pressure:

$$\Delta P = \frac{R}{V} \Delta T$$

where R is the thermodynamic constant of perfect gases.
If at least one of the contacts is hollow, excess pressure causes the gas to flow off to the zones still cold in the device (downstream volume).
As it flows off, the gas cools the arc which has formed between the hollow contacts acting as exhaust nozzles.

Arc guidance

The situation described above is somewhat idealised. If precautions are not taken, the arc can move away from the axial position, for example under the effect of electrodynamic forces (see fig. 6). It is then outside the path of the exhaust gases, or at least in a zone where gas rate is too low to have the slightest effect.
To ensure this does not occur, the arc must be controlled.
There are two possible control modes: mechanical and magnetic.

■ mechanical control
This mode, which is the most efficient, the most reliable and the least tricky to implement, is directly derived (see fig. 7) from the arrangements used in piston-operated circuit-breakers.
However, as regards breaking, it has a certain number of drawbacks:
□ presence of the insulating control part (nozzle) deforms the electric field and results in large opening gaps and high contact speeds, thus increasing the energy required for mechanical control,
□ only a small part of the arc is found in the upstream volume, in a very off-centre zone: the rest of the arc is partly in the nozzle.
Energy efficiency is reduced accordingly, as are also excess pressure and blowing, particularly for small currents.

■ magnetic control
The arc, placed in the magnetic field of a magnet or coil, is centered with the axial component and rotates under the effect of the radial component (see fig. 8).
Compared with mechanical control, it presents certain study and development problems:
□ the magnetic barrier is immaterial and hard to grasp. In particular, it contains areas of instability which are hard to show up. It can only be perceived through calculations, measurements and simulations,
□ inter-contact gaps are limited (the magnetic field decreases considerably as the coil is moved away).
However, on the other hand, it has certain decisive advantages:
□ the electric field is not disturbed by the presence of an insulating part, and dielectric withstand is considerable even for small travel. This results in:
- the possibility of using SF6 under low pressure,
- simplified breaking of capacitive currents,
- possible minimisation of contact travel and thus reduction in the control energy required,
□ easier arc-gas energy exchange.

■ arc rotation
This considerably reduces contact wear, thus increasing the number of operations (electrical endurance). This extremely interesting technique is used since 1980 by the Rollarc circuit-breakers/contactors (see "Cahier Technique" n° 123) and is one of the major consequences of magnetic arc control.

By combining this control mode with expansion blowing, circuit-breaker performance can be considerably enhanced: auto-expansion circuit-breakers can thus work in HV unlike those using only the rotating arc.
In actual fact, expansion results in thorough sweeping of the inter-contact zone, since, under the effect of the gas stream:

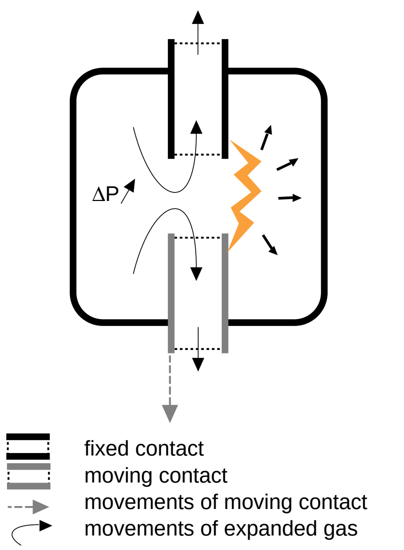


fig. 6: example of an uncontrolled arc.

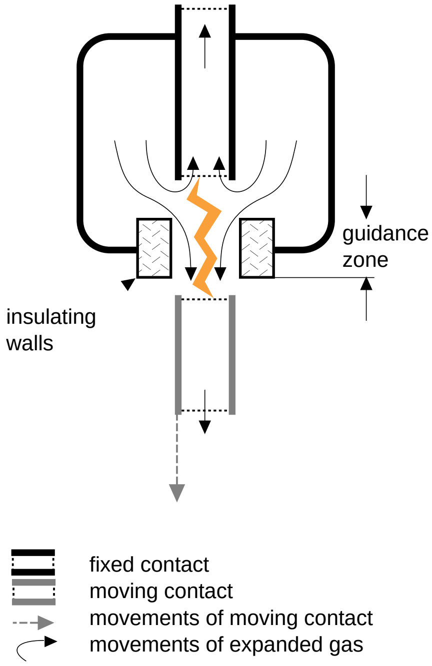


fig. 7: mechanical control by insulating wall .

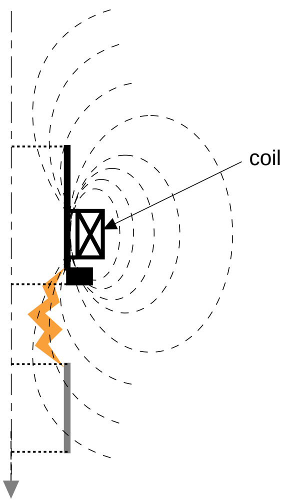


fig. 8: arc control by the magnetic field of a coil (half-section).

□ the metal particles from the electrodes are discharged in the nozzles ;
□ around current zero, the arc roots are pushed back into the tubular electrodes (nozzles) which are then cooled more quickly (see fig. 9).

Development means

The decision to use only the energy developed by the actual arc and the magnetic forces induced by the current to be broken required the use of sophisticated development tools.

For example:

■ Optical methods were used for study of gas flows and arc visualisation.The gas flows, whether or not an electric arc was present, were visualised by strioscopy.
This technique can be described as follows: the hot gas forms a medium with a variable refraction coefficient which causes the light beam to deflect. A large number of configurations are possible: designers have chosen the one shown in figure 10.
The acousto-optical modulator at the argon laser outlet is used to artifically increase the performance of a mechanical camera with rotating prism. This camera is used without its prism, with the modulator directly controlling exposure time and shooting speed (typical values are 0.5 and 20 ms respectively). It is thus possible to observe arc centering and its elongation in the nozzles around current zero (see fig. 9).

Cold gas schlieren study (without electric arc) revealed areas of turbulence, separation, shock waves and, as shown in figure 11, the gas flow streams.
Differential interferometry, far more flexible in use than classical configurations (Michelson, Mach-Zender...) and less affected by alignment faults and vibrations, enables comparison of gas flow rates in a variety of geometries, both symmetrical and asymmetrical (see fig. 12 page 10).

Presence of an arc considerably reduces the advantages of using some of the above methods, in particular interferometry, due to the appearance

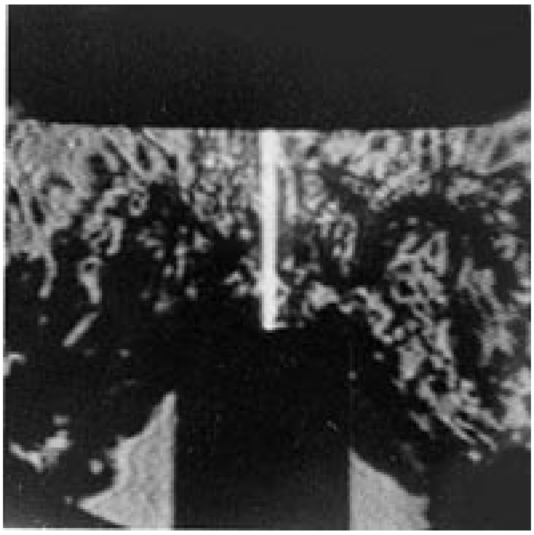


fig. 9: arc centering around the current zero.

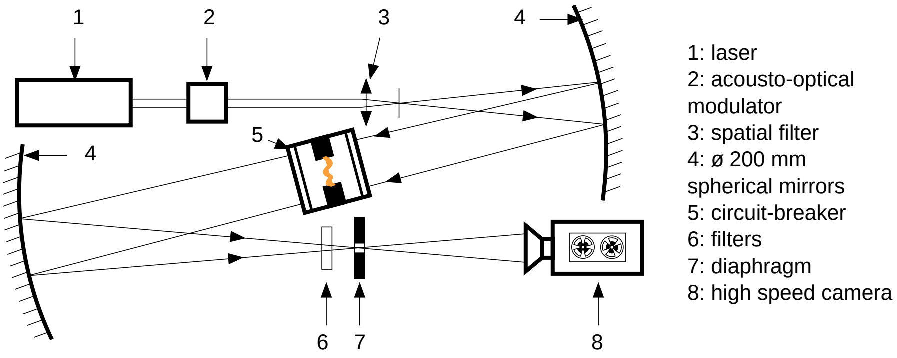


fig. 10: optical strioscopy device.

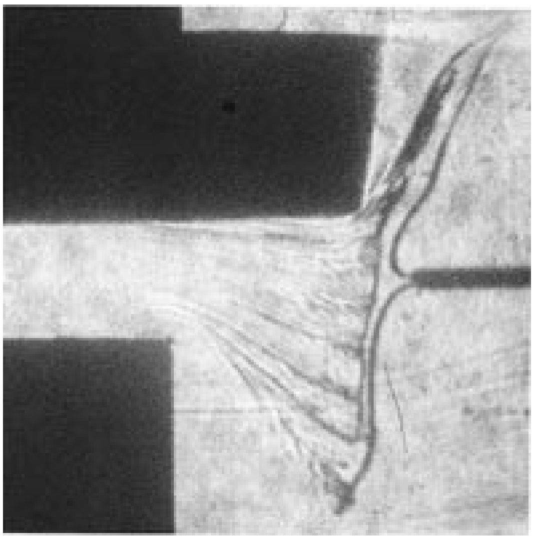


fig. 11: visualisation of gas flow-off on contact opening (the right of the photo shows resistant wires for heating ambient gas).

of highly turbulent zones. The interference fringes deform, blur and even disappear altogether.
On the other hand, other direct observations on the arc are now possible, namely measurement of its radiation or temperature by spectrography. The remarkable reproducibility obtained on the study mock-up led to the results shown in figures 13 and 14. These experiments made possible observation of temperature and electronic density to values approaching the current zero.

■ scientific computing was used to optimise certain thermodynamic parameters affecting breaking.
In actual fact, complexity of phenomena makes it impossible for them to be fully understood by the various possible measurements and observations.
Moreover, most of these measurements are cumbersome and can only be implemented on specially designed mock-ups. They are not suitable for studies with parameter variation.
A thermodynamic model has thus been designed to express the main values: rate, gas pressure, temperature,.... according to the geometry of the device and the current flowing through it. The measurements, both in cold gas and arc presence, are used to «adjust» the model (and also to increase understanding of the physical phenomena involved!).

Calculation results can be indirectly checked and readjusted, if necessary, by comparisons with the experiment if these are possible. This is the case for arcing voltage and pressure, which can both be calculated and measured (see fig. 15 and 16).
Agreement between measurements and calculations ensures sufficient confidence when the results relate for example to speed and flowrates which are practically impossible to calculate in experiments.
This modelling also considerably reduces development times and costs.

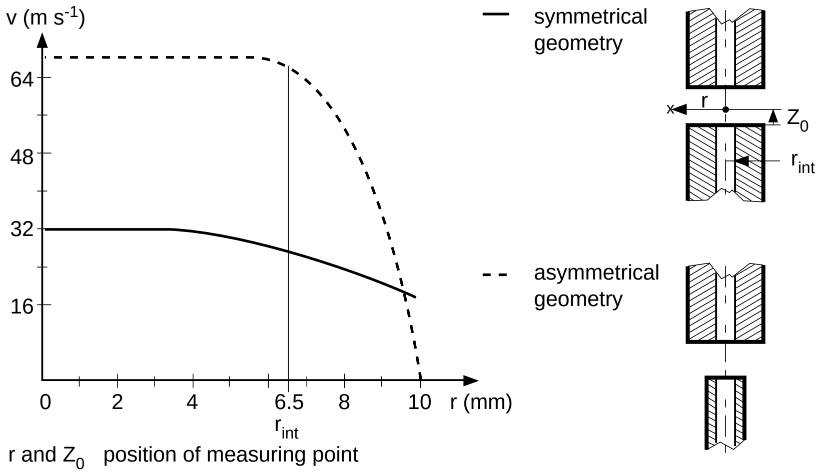


fig. 12: SF6 radial flow rate, measured by differential interferometry.

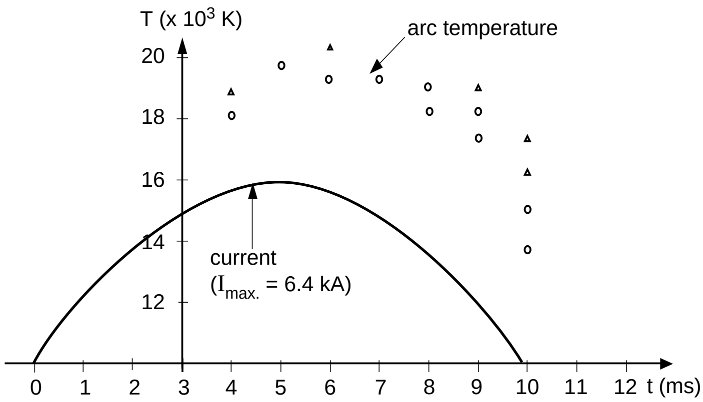


fig. 13: arc temperature.

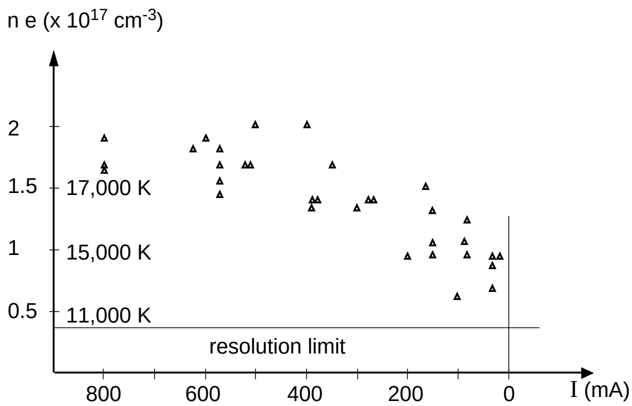


fig. 14: electronic density n of arc around the current zero.

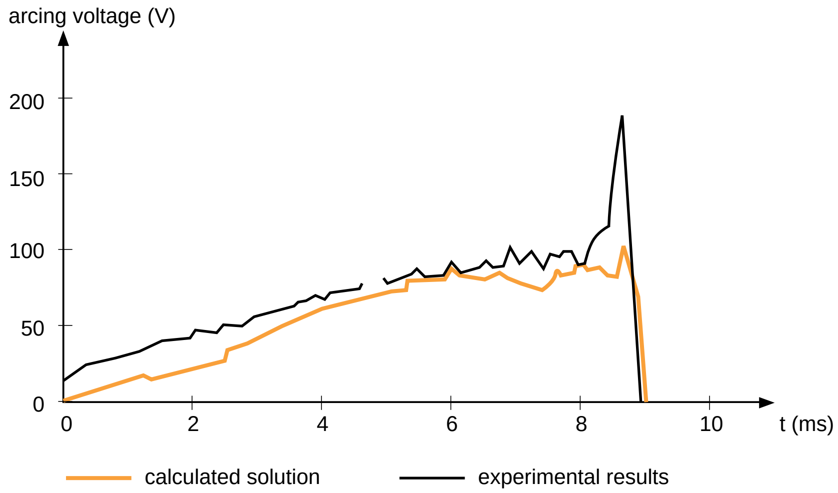


fig. 15: comparison between experimental and scientific calculation results (NS2 software) on arcing voltage.

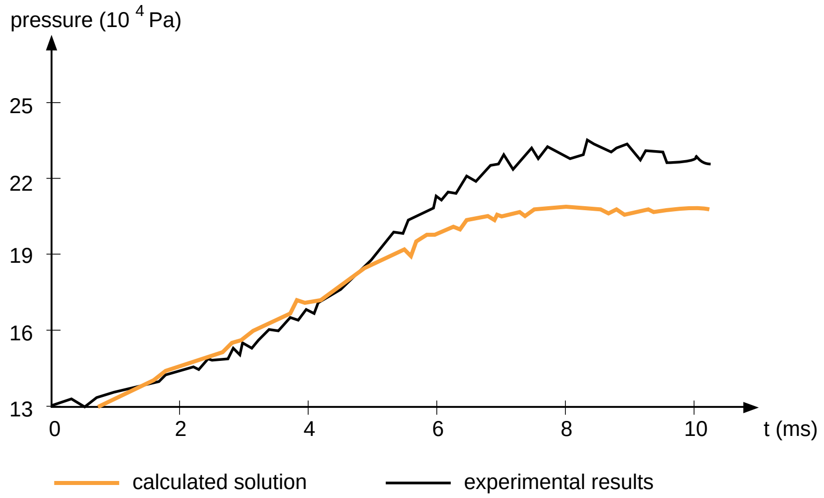


fig. 16: comparison between experimental and scientific calculation results (NS2 software) on pressure build-up in the upstream volume.

3. SF6 auto-expansion circuit-breaker

Command of auto-expansion has enabled marketing, in both MV and HV, of products adapted to needs.
The circuit-breaker of the RM6, the LF and the SB6 circuit-breakers illustrate this perfectly.

the circuit-breaker of the RM6 200 A - 24kV/16kA

The RM6 is a «fully SF6» device (GIS switchgear as in standard IEC 298) with built-in functions and compact dimensions. Its purpose is to ensure maximum continuity of service of ring main distribution systems.
It is fitted with two ring switches and a circuit-breaker (or a fuse-switch), designed to create a bypass on the ring and/or to perform connection and protection of a MV/LV transformer (see fig. 17).

The rated values of the circuit-breaker incorporated in the RM6 are 200 A, 24 kV. Use of auto-expansion provides this circuit-breaker with several important technical advantages:

- ■ it is placed, like the ring switches, in an enclosure filled with SF6 at atmospheric pressure (see fig. 17);
- ■ there are very few parts, e.g. one single part performs all the following functions:
  - □ current flow,
  - □ breaking (circuit-breaker moving contact),
  - □ insulation and earthing (circuit-breaker open);
- ■ total control energy (C-O) does not reach 100 joules;
- ■ volume less than that of the switch + fuse. It is installed in the place of the «feeder» switch.

This simple, compact, economic circuit-breaker, with a breaking capacity of 16 kA in 24 kV and 20 kA in 17.5 kV has achieved the target objectives (see chapter 2) in this MV application.

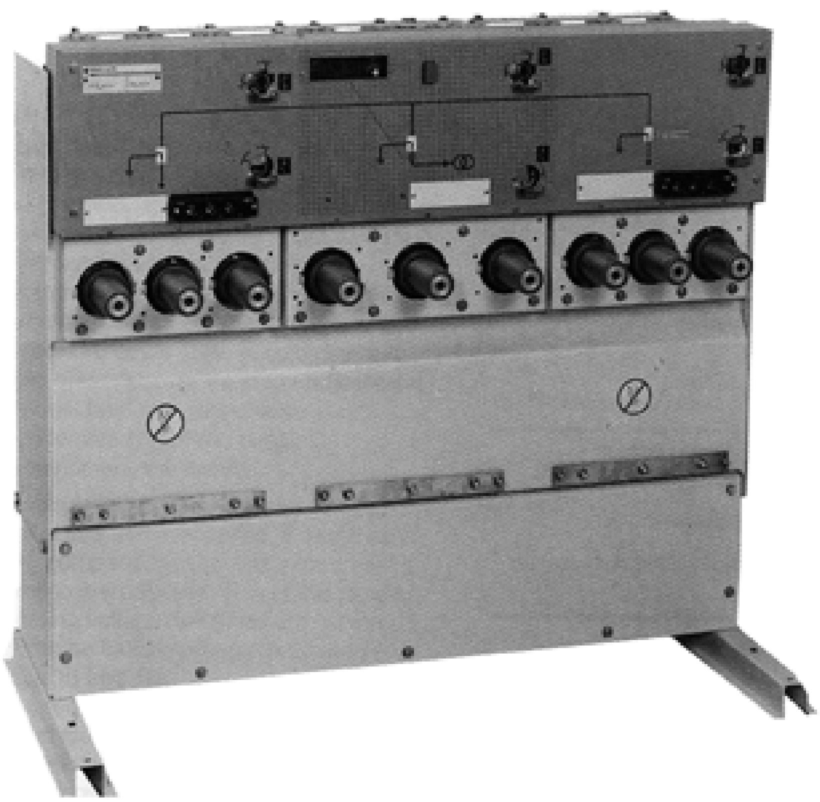


fig. 17: equipment for MV distribution for ring main distribution system; the output, protected by the circuit-breaker is placed in the centre (RM6 - Merlin Gerin).

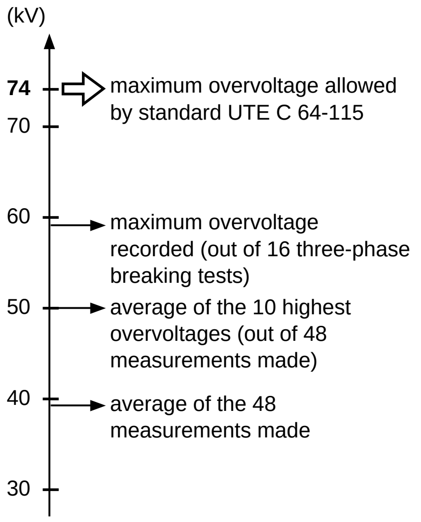


fig. 18: result of tests carried out as in standard UTE C 64-115 with a SF6 auto-expansion circuit-breaker (circuit-breaker of a RM6 - Merlin Gerin).

As regards the «minimum switching overvoltage» objective, the performance obtained on de-energising a slightly charged transformer is considerably better than the requirement of standard IEC 298 (see fig. 18) and makes the RM6 circuit-breaker one of the best on the market.

the LF circuit-breakers 630 to 3,150 A, 7.2 kV/ 50 kA, 17.5 kV/31.5 kA

These circuit-breakers form a range of devices designed for the protection of public and industrial distribution networks. They can be used in fixed or withdrawable version, in functional units in metallic enclosures (module, with compartments or metalclad) (see fig. 19).
Application of auto-expansion ensures them considerable advantages, which include increased endurance and safety. To give some examples:

■ the reduced energy involved during switching operations and the little force required in the open and closed positions, result in high mechanical endurance (10,000 operations), far exceeding user needs;

■ arc rotation on the electrodes results in low, even wear providing the device with outstanding electrical endurance (possibility of breaking up to 40 times the rated short-circuit current);

■ just as in the above examples, the capacitive and inductive current operations are performed without rearcing or repeated disruptive breakdown and without any overvoltage damaging for the network and the equipment it supplies;

■ SF6 pressure is only 100 kPa (relative), resulting in increased reliability as regards stability of performance over time and in greater safety.

the SB6 circuit-breaker 2,000 A - 72 kV/31.5 kA

This circuit-breaker, designed for HV substation equipment, can be used in conventional outdoor substations (see fig. 20) or incorporated in metalclad substations.
This circuit-breaker owes its simplicity to:

■ electromechanically, a control energy (C-O) of 520 joules (traditional MV level), resulting from the minimum travel and lightness of its moving elements, presenting obvious reliability advantages.

■ as regards breaking, a very «clean» de-energising of the off-load lines, as shown in figure 21 page 14, on which no transient overvoltages are visible, despite the choice of the most unfavourable opening time (0.5 ms before current zero). It is the very fast increase in inter-contact dielectric strength with the opening gap which is decisive. Distribution of electric field and absence of insulating parts (no blowing nozzle) make this possible.
This off-load line breaking test is part of the certification tests stipulated by standards for circuit-breakers.

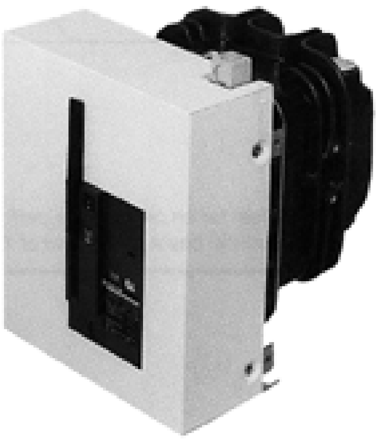


fig. 19: auto expansion LF circuit-breaker.

development and certification tests

Before marketing a circuit-breaker, manufacturers must:

■ carry out a large number of tests on development. This is despite modelling and simulation of physical phenomena which considerably aid development and thus reduce the number of tests.

■ ensure standards are complied with by tests carried out by a testing station accredited by one or more of the national organisations (refer to glossary).

These tests result in a certificate of conformity to the various standards.
In MV and HV, reference standards are IEC 56 and 694 and ANSI C37-04 and onwards. EDF also requires additional tests according to its own specifications.

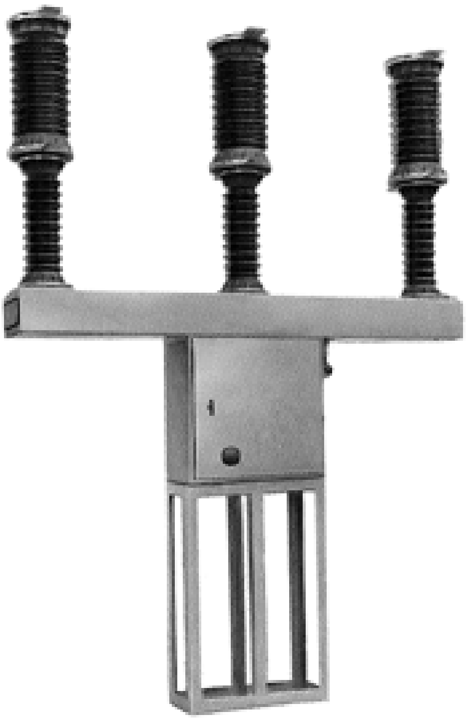


fig. 20: circuit-breaker for HV substation equipment (SB6 circuit-breaker - Merlin Gerin).

To give an example, when the SB6 circuit-breaker was released, official approval reports required around one hundred breaking tests.

■ these official certificates apart, experience leads the most reliable manufacturers to also perform a large number of additional tests. Their purpose is to ensure that circuit-breaker behaviour is faultless in special network configurations and for certain loads. The number of tests performed is even greater in the case of new breaking techniques.

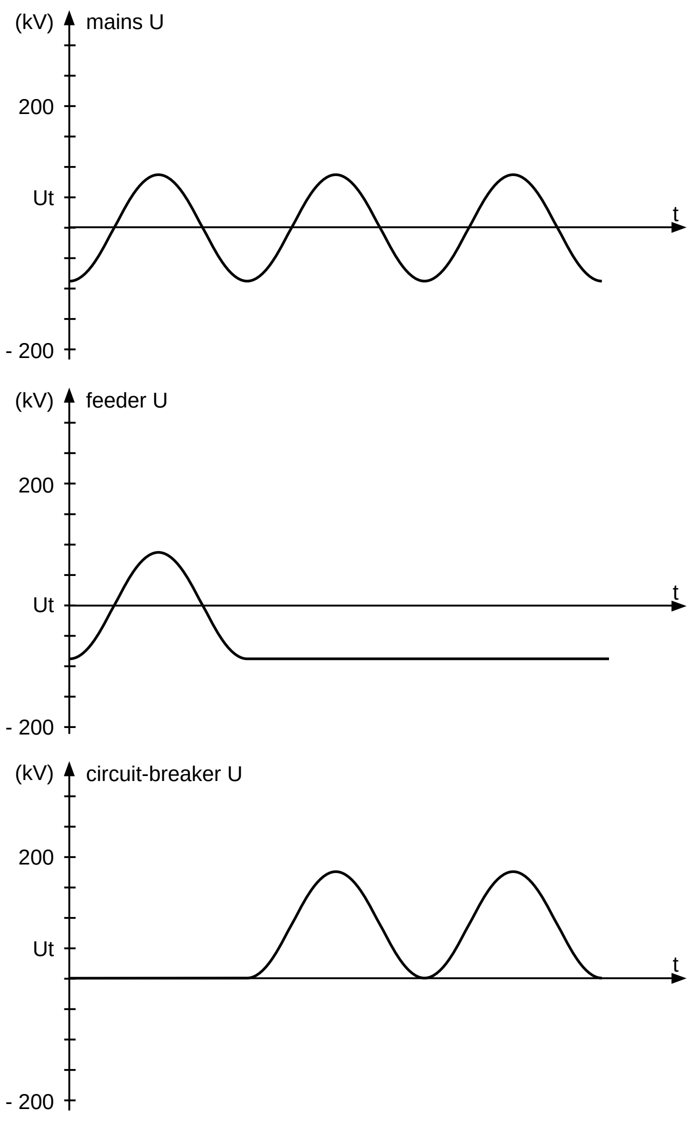


fig. 21: breaking test for an off-load line performed with a SF6 auto-expansion circuit-breaker: the measuring channel has a pass-band of 10 MHz (SB6 circuit-breaker - Merlin Gerin).

4. conclusion

SF6 auto-expansion breaking enables production of simple, reliable circuit-breakers with auto-adaptive, «gentle» breaking. The «no external power supply» principle, together with the absence of contrivances such as surge arresters, resistors and capacitors, mean that auto-expansion is the breaking technique which makes you forget the circuit-breaker.

Let us stress its qualities once again:
- clean breaking (all loads);
- excellent reliability (few moving parts and reduced control energy);
- minimum maintenance and low SF6 pressure;
- high electrical endurance;
- compact dimensions.

Today no theoretical or technological limitations prevent this technique from being used in MV and HV. The main factor stopping it being generalised is the length and cost of the development and tests.

SF6 circuit-breakers using auto-expansion combined with network digital protection and control/monitoring systems guarantee, both now and in the future, maximum availability of electrical power.

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■ IEC 694: Common clauses for high-voltage switchgear and controlgear standards.

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Réal. : Illustration Technique Lyon - Photo. : Merlin Gerin
DTE - 03/95 - 2500 - Imp. : Clerc