

fault arcs on busbar sets and switchboards

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summary

The probability of appearance of a fault arc on a set of busbars cannot be considered as non-existent. The behaviour and speed of arcs have been analysed by a high-speed photography system. It appears that the damage produced by the arc is inversely proportional to its speed and its freedom of movement. Switchboards manufacturers, contractors and operators must take all possible precautions to reduce the possibility of arcs occurring, and their consequences.

If the electrical installation is correctly designed, built and maintained, the appearance of a fault arc between switchboard busbars is an extremely low probability accident.

The statistical data collected over a long period and for a large number of installations in service demonstrate that this probability is not, however, null.

Because of the grave consequences resulting from arc-over in a switchboard : plant production shutdown, repair costs and accidents to personnel, it is the switchboard designer's, installer's and operator's responsibility to take all measures to ensure that the possibility of arcs originating is very low, and, in such events, that the consequences of the incident are reduced to the possible minimum.

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1. the origins of a fault arc

The causes for the occurrence of a fault arc in an installation can be broken down into three categories :

- evolutive causes ;
- mechanical causes ;
- voltage surges.

evolutive causes

These result from a gradual decrease in the inter-phase or inter-phase to ground insulation resistance.

This decrease can be the result of deposits which, subsequent to exceptional humidity conditions, can result in the formation of a superficial resistance bridge such that a conductive path on the surface of insulators can be created.

Depending on the type of insulators, this initial fault may be self-eliminating, or become worse, resulting in the creation of a fault arc.

This phenomenon is sometimes observed when an installation is switched on again after being shut down for a period of several days, during which condensation may have occurred due to the fact that the installation temperature is no longer higher than ambient temperature. In particular, this applies to glass-making installations, in which the atmosphere carries sodium carbonate dust, and in which the risks of hygroscopic variations are high.

The final result will be the same if the superficial pollution of the insulators results from splashes of fluids containing electrolytes. The accident may pass unperceived, and occur during transport and handling of the installation components. The defect will be revealed later during operation under exceptional hygroscopic conditions. This also applies to condensation on equipment stored in coastal areas, and which is incorrectly protected.

The gradual degradation of the insulation may also result from accidental local heating due, for example, to incorrect tightening or gradual loosening of a connection. The increase in temperature immediately round the defective point can entail decomposition and progressive carbonization of the adjacent insulators, resulting in a fault arc, first of all between phases, or between phases and ground, and degenerating into a three-phase fault.

mechanical causes

These result from the presence of a conductive element foreign to the structure of the installation itself.

An example of this is incorrect work effected by operating staff : the instructions concerning the precautions to be taken during work effected on low voltage parts are not always strictly observed.

For example, it has been observed that, in order not to disturb overall operation of an installation, an electrician desiring to perform a check opens the back panels of a switchboard, and considers that it is possible to work on the busbars rendered accessible, taking adequate precautions. It simply requires a tool to slip or escape from his hands, or a tester light (prohibited) to explode, resulting in general arc-over, risking serious burns for the imprudent technician.

The result would be identical if a « forgotten » conductive object in the top part of a switchboard (tool, portion of busbar, nut, washer, metal shim, etc.) moved gradually due to the effect of vibrations and fell between two bars, or between two cable attaching bolts. Similar incidents would result from the presence of an animal inside a switchboard (cat, bird, rat, etc.).

voltage surges

Only high value voltage surges cause arc-over in a switchboard which has been correctly designed and installed. However, such exceptional incidents may occur, in particular with LV.

Voltage surges reaching 8 to 10 kV have been detected on LV networks. These result from transmission of normal voltage surges via the MV/LV transformer capacitances, occurring in MV, for example in the event of cutoff of a magnetizing current on an off-load transformer. Installation of surge arresters on the LV terminals of the transformer is the best method of preventing this type of incident.

2. arc fault behaviour

The movement of a fault arc along the busbars of a switchboard is totally random. However, general laws can be defined to explain and forecast arc behaviour.

arc characteristics

First of all, it is the very nature of the arc itself which provides an explanation of its behaviour : an electric arc consists of a column of conducting gases (plasma) taken to high temperature : 6 to 12 000° K for arcs involved in switches and in faults.

Its form, which is random, generally does not have the shape of an arc, as might be supposed from its name ; its cross-section can be considered as circular in the absence of external stress. It results from a balance between the internal pressure of the hot gases in the column and the magnetic striction due to current flow.

Transmission of the current is provided within the arc by free electrons moving in the opposite direction to that of conventional current flow.

The positive ionized particles in the column, which are almost equal in number to that of the electrons, carry only a very small part of the current, due to their mass which is much higher than that of electrons. These have the effect of compensating the space charges of the electrons.

The arc can therefore be assimilated to a gas conductor, the shape of which adapts instantaneously to the electrodynamic forces acting upon it ; mobility is very high due to its very low mass.

Both ends of an arc column are always connected to solid (or fluid) conductors by the arc roots. These are cathodic and anodic areas of very low length (10^{-4} cm) which are the location of phenomena essential in maintaining the arc process.

These arc roots form extremely mobile electrical connections on the surface of the conductors carrying the current, and result in superficial fusion of the conductors.

The arc is an electrical conductor, the inherent resistance of which is high and highly fluctuating, in particular as a func-

tion of the current flowing through it. It is more practical to calculate the arc voltage, or voltage drop across the arc, than its resistance ; the arc voltage, the minimum value of which is of the order of 20 to 30 V, reaches values of between 100 and 300 V for fault arcs.

An arc can be expressed by the formula $U_a = U_e + \ell E$, in which :

- U_e is the sum of the cathodic and anodic voltage drops, on average 20 V
- ℓ is the length of the arc (cm)
- E is the potential gradient (V/cm) of the arc column.

For an arc in quiescent, naturally cooled air, E is 15 to 20 V per cm, but can reach 50 V per cm as soon as the arc is cooled.

arc movements

Propagation of a fault arc along a switchboard busbar set is the result of electrodynamic forces applied to the arc by the conductors along which it moves, or by any other adjacent high field conductor.

The direction of movement of the arc is such that the flux covered by the loop formed by the arc and its conductors tend towards a maximum (fig. 1).

Thus, as a general rule, **the arc runs along the bars away from the source, even if this movement obliges it to descend vertical bars.**

The thermal chimney effect, which tends to make the arc rise, is generally negligible with respect to the electrodynamic forces which are proportional to the square of the current.

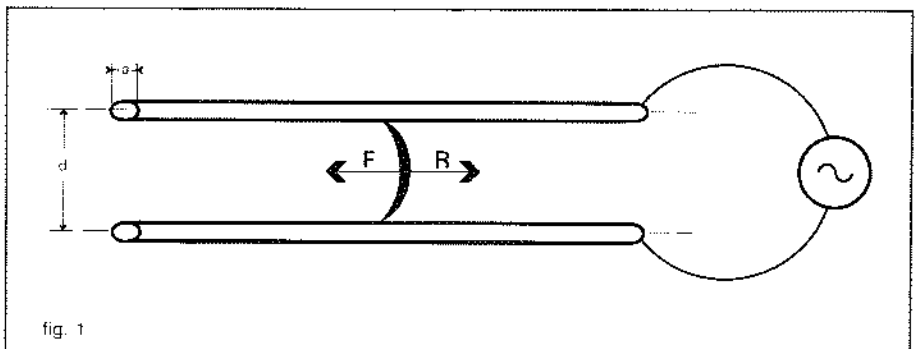
The electrodynamic force F applied to an arc across two parallel conductors is (7) :

$$F = \frac{2}{10^7} I^2 L \left(\frac{2d + a}{a} \right)$$

Due to force F , the arc attains a speed V limited by the resistance R of the air in which it moves. This resistance R is of the form $R = K \cdot V^2$, in which K is a coefficient depending on arc geometry, assimilated to a solid body. The movement rapidly becomes uniform when $F = R$, arc speed being then :

$$V = \sqrt{\frac{2}{10^7 K d}} L \left(\frac{2d + a}{a} \right)$$

It should be noted that **the speed of movement of the arc is proportional to the instantaneous current flowing through it** ; this speed decreases slightly when the length of the arc increases, i.e. with bar spacing, itself a function of working voltage (4).



experimental checks

Measurement of the speed of arcs along busbar sets, together with their behaviour with respect to changes in busbar direction or isolating obstacles encountered along their paths have been the subject of a series of tests (fig. 2). In order to collect as much information as possible, an optical recording system was used in addition to conventional oscillographs.

Rather than use a high-speed motion picture camera (5 to 8 000 frames per second) which would, however, have given satisfactory information, it was preferred to use high-speed photographic methods, due to the ease with which this method can be used and results analysed, for a high number of successive tests.

This method consists in superimposing a series of images recorded at a high rate, of the same subject, the set of busbars, on the same negative; when the arc moves rapidly, its position, at the location in which it is found, is photographed every 100 th of a second.

Simply by examining the photo obtained, it is easy to determine average speed, and to interpret the behaviour of the arc with respect to multiple busbar set configurations and obstacles placed along its path.

In particular, color negatives offer a clear differentiation between the arc column itself, the ionized clouds and smoke surrounding it.

From the practical view point, photographic recording is simple: a conventional camera covers the visual field in which the phenomenon to be recorded, the arc, takes place. The normal shutter is opened a few instants before the test, and closed shortly afterwards. During this period, a shutter disk, driven at 50 rpm by a small synchronous motor, rotates in front of the lens. Slots are cut radially in the disk, the passage of which before the lens corresponds to taking of a photo, while the exposure time corresponds to the width of the slot.

Several disks enabled photography at rates of 50 to 300 exposures per second, the exposure times of which varied from 0.5 to 2 milliseconds.

speed of movement

The arc moves at high speeds of the order of 200 to 250 metres per second for currents of approximately 15 to 20 kA rms, along a set of LV busbars separated by 300 mm of air.

For AC, this is the average speed. In practice, the inertia of the arc is so low that the instantaneous speed cancels out at the same time as the current passes through zero (or extinguishes momentarily), then increases again to reach a maximum corresponding to the peak intensity of the current sinewave. This phenomenon was highlighted by photographs taken at a high rate (200 to 300 exposures per second) during single-phase AC tests.

damage due to the arc

If the fault arc is propagated freely along busbars without any discontinuity or excessively sudden changes in plane, without encountering metal obstacles or insulators, its passage causes almost no damage. The arc roots move in successive jumps, leaving insignificant traces, in the form of small circular stains a few mm in diameter.

Conversely, if the arc is hindered or stopped in its travel, even for a few hundredths of a second, it then causes serious damage: fusion of metal and combustion of insulators.

obstacles along the arc path

The behaviour of the arc with respect to discontinuities in the bars along which it is propagated is, however, relatively random, in the same manner as the obstacles it encounters.

Thus, a sudden change in direction along a set of linear bars can cause the arc either to stabilize on the sharp edge formed by the bars, or continue propagation along a new direction imposed on it.

To halt arc propagation, the most appropriate process is to run the busbars through an insulating screen. This will fulfill its function correctly only if it forms a veritable feedthrough moulded around the conducting bars. A clearance of the order of one millimetre between the insulating screen and the bar metal is sufficient to enable ionized gases to cause arc-over again on the other side of the screen.

the various effects of arc

The thermal effect: this is the most important manifestation of the electric arc:

The calorific energy $E_a = U_a \cdot I_{cc} \cdot t$ is proportional:

- to the arc voltage U_a , of 100 Volts or more

- to the rms current of the fault I_{cc} , generally some tens of thousands of amperes for LV, while less for MV

- the duration of the fault t , controlled by the intervention time of the associated protection relays and circuit-breaker.

The heat given off melts the metal, carbonizes insulators, heats the surrounding air, the pressure of which increases suddenly if the surrounding volume is restricted. Too often, the enormous quantity of heat given off by fault arcs is underestimated. As an example, a fault current of 10,000 Amperes for a period of one-tenth of a second is all that is required to melt half a 150 sq.mm cross-section cable.

The pressure effect: this results from very rapid heating of a limited volume of air, causing those who have witnessed it to compare a short-circuit to an explosion. Few enclosures or switchboard doors withstand such internal pressures, resulting in increased damage to installations. An arc flashover is also accompanied by **impressive noise**, resulting from the sudden variation in pressure. For AC, this noise would be even a roar.

The luminous effect of an arc is well known, but, in addition to its extreme intensity, it consists partly of ultraviolet radiation liable to affect the vision of a person located nearby, but above all increases the surrounding ionization.

The ionization effect can cause repeated arc-over between parts under voltage, separated by an insulating interval which, under normal atmospheric conditions, would be correct. These repeated arc-overs result in secondary arcs, independent of the initial arc, which are propagated along different portions. This explains the multiple arc-overs observed after a strike in a switchboard, rendering it difficult to locate the exact origin of the fault.

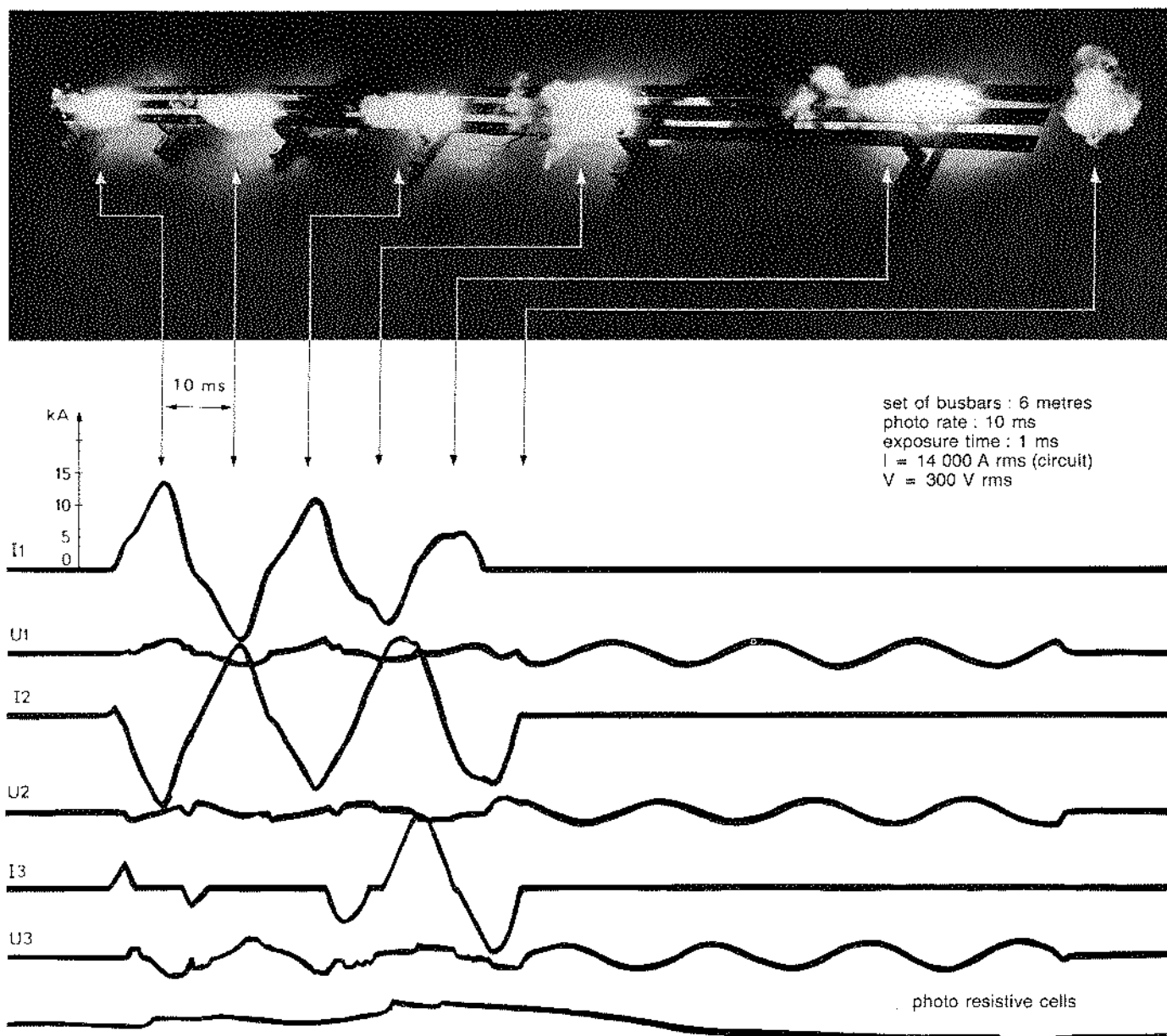


fig. 2. oscillogram and photograph corresponding to an arc propagation test on a 14 000 A rms 300 V circuit.

3. reducing the probability of arcing

The steps to be taken must meet the corresponding risks; these are of three types:

■ type 1 risks:

These result from the actual construction of the overall installation: insulator quality, minimum insulating distances, efficient tightening of connections, rigidity of bars between mountings, bar behaviour in the event of eventual current surges (overheating, resonance), access of animals to parts under voltage.

■ type 2 risks:

These result from more or less foreseeable accidents: sudden ingress of water or water vapour in a switchboard, shock from vehicles or loads, resulting from mishandling, excessive vibrations due to the proximity of certain machines.

■ type 3 risks:

These result from work carried out by personnel.

Type 1 risks can be eliminated by careful construction and by complete checks at end of construction at the manufacturer's works and again prior to energizing on site.

For these risks, the importance of the actual design of the equipment should be noted: the operational safety of installations depends on the technical value and know-how of the design office personnel.

Type 2 risks, although impossible to eliminate totally, can, however, be reduced by choosing the layout of the various parts of the installation.

The special case of switchboards installed aboard ships should also be noted: arc faults due to the arrival of sea water on the bars through ventilation ducts, or due to abundant condensation resulting from a heavy steam leakage have been observed.

These accidents can be avoided by a complete preliminary survey of these external risks and the methods used to eliminate them (6).

Type 3 risks are directly related to the drawing up and respect of personnel maintenance and operating instructions. The competence of the personnel authorized to work on the equipment should be guaranteed. The overall safety of the installation itself, or a plant, and of course, personnel safety depend directly on the seriousness with which personnel approach their work.

It is always possible to design and produce switchboards whose busbars and branch circuits can be protected from unwanted tampering by personnel.

One method consists in placing all bars under voltage in metal sheaths, thus enabling personnel to work safely on adjacent control circuits.

The safest method, but also the most expensive (widely practiced in the United States) consists in completely sheathing all busbars, connections and connection parts by coating the conductors in an insulator such as Rilsan, and wrapping all other parts under tension with insulators after installation.

4. limiting the consequences of an arc

In spite of all the precautions taken, it is possible that a fault arc may occur, but with a very low probability; if so, it is necessary to reduce the damage that may be caused, so as to be capable of rapidly and inexpensively re-establishing energy distribution.

Various methods can be applied to this, resulting either from switchboard construction methods, or the design of the diagram or protective devices used.

reducing the fault current

The thermal effects are proportional to this short-circuit current I_{sc} , which often, in LV applications, can be considerably reduced by the use of limiting circuit-breakers (9) (10).

It is therefore recommended to use this equipment for switchboard incomer circuit-breakers, where their characteristics (range, partial selectivity) are compatible with the installation.

But, in LV networks in which high power is provided by several transformers or generators connected in parallel, the short-circuit current value on the busbar sets can reach or even exceed 100,000 A rms. This involves a risk of heavy damage in the event of a switchboard fault.

This risk can be considerably reduced by adopting distribution diagrams similar to those used aboard ships, and whose high degree of safety is well-known.

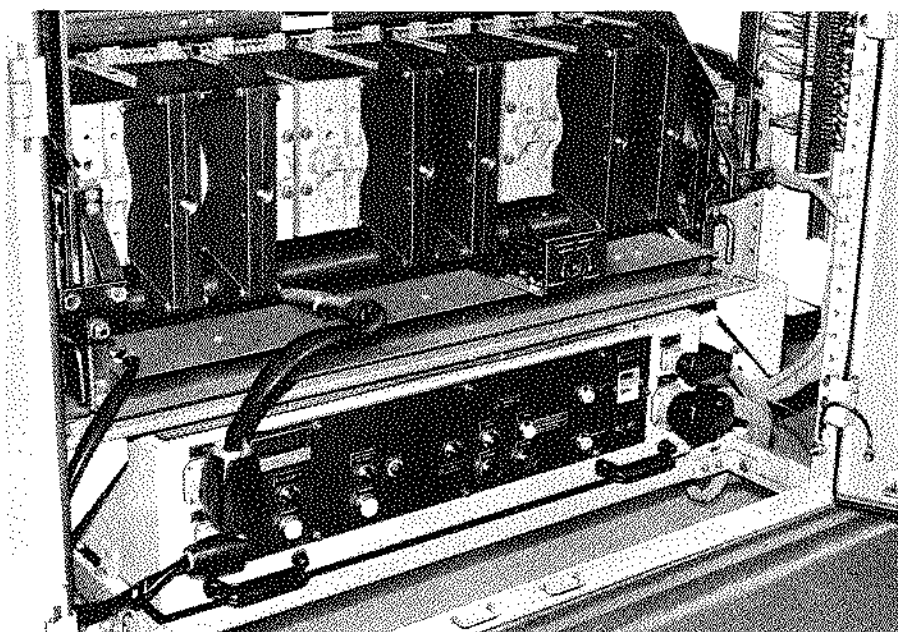
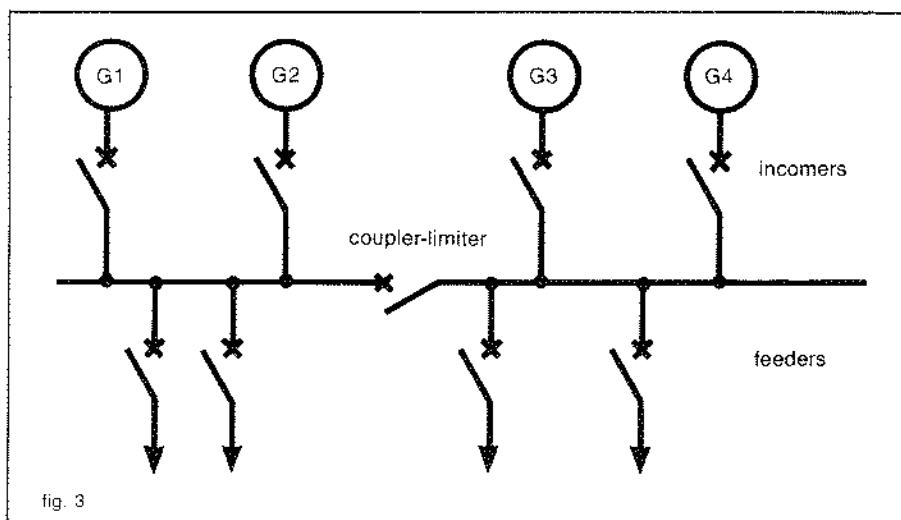


fig. 4. ultra high-speed coupler-limiter DURT 6000 installed in the container ship FORT DESAIX

The generators are distributed over permanently connected half busbar sets, for operational requirements, through a coupling circuit-breaker (fig. 3).

This high rating device, 3 000 to 6 000 A, is generally highly limiting, calling for a design principle much different from that used in conventional limiters. In fact, the limiting capability of conventional limiters decreases as the rating increases; there is no equipment of this type beyond 2 000 A. Therefore, to resolve this problem, Merlin Gerin have developed an ultra high-speed limiter circuit-breaker DURT, the opening time of which is less than one millisecond (fig. 4).

The short-circuit current on the busbar set is reduced almost to half of its calculated value with all sources operating in parallel. This reduces risks in the event of a major switchboard incident.

Moreover, this major decrease in short-circuit current proportionally reduces the break capability of all feeder circuit-breakers; the economy thus obtained on the equipment compensates the supplementary cost of a limiting coupling circuit-breaker.

reducing fault duration

The thermal effects are also proportional to this duration t , which is attempted to be reduced by eliminating the fault as rapidly as possible. But, the equipment used for this purpose is source circuit-breakers, the selectivity requirements of which often call for time delays. The least that can be done is to ensure that the delay settings are as low as possible, without withdrawing apparent safety margins from these times, which would be regrettable in the event of short-circuits on a set of busbars.

It has been demonstrated that a fault of 20,000 A, which is relatively low for LV, propagates at 300 metres per second, almost at the speed of sound; therefore, the arc can cover 45 metres over the first 150 milliseconds of the time delay.

In order to remedy this situation, Merlin Gerin have developed a new system: **logic selectivity** (8), enabling conservation of absolute selectivity without being obliged to increase circuit-breaker delay, insofar as these are installed further up system, a principle already used in chronometric selectivity.

consumable screens and arc traps

It is possible to conceive a busbar arrangement such, that after a certain travel, the arc remains « locked onto » one end, without propagating any further: then, the **consumable screen**, the thickness of which is determined as a function of the probable power to be absorbed, is inserted in front of the arc.

This screen may be either metallic: the arc will then be absorbed in melting the metal, or a mineral insulator with sufficient resistance to heat. By combustion, an organic insulator will produce gases having dangerous effects. It is also possible to place parts of appropriate shape on the bars, the purpose of which is to direct the arc in a direction in which its consequences will cause less damage and will, at least, be controlled by a consumable screen. These devices are known as « **arc traps** ».

feedthrough, screens

Division of a set of busbars into several sections, as described above, can be advantageously accompanied by efficient physical insulation between the various sections. Feedthroughs of this type form screens against which the arcs stop, but their composition must be such that they withstand arc heat for the required time.

advantage of enclosed unit cells

It sometimes happens that a fault arc occurs on an item of equipment subsequent to a tool or piece of metal being left on the surfaces of the equipment. Generally, the arc thus created finds adequate conditions for local persistence, and remains « locked » to the equipment involved, while strongly ionizing adjacent zones. The result of this is that, if the item of equipment is located on a framework or structure, ionization can entail arc-overs on adjacent circuit-breakers and busbars resulting in general arc-over throughout the installation. Conversely, if each item of equipment is separated from the remainder of the installation by metal walls, the risk of fault generalization is eliminated.

Each operation device is installed in a unitary cell, which nevertheless contains a neutral zone enabling expansion of gases to prevent pressure surges.

The input and feeder terminal feedthroughs are made by means of insulating feedthroughs, limiting the consequences of an arc to the inside of the cell in which it occurred, or protecting the cell against arcs of external origin.

Device operating manoeuvres (opening-closing), as its line and load side disconnection (withdrawing), are made with the door closed.

Since withdrawing precedes opening of a cell door, the personnel working directly on the equipment (for maintenance, testing or replacement) is therefore out of range of the busbars and protected from flashes from a cutout device located in an adjacent cell.

resistance of HV switchboards to internal arcs

For high safety installations, it has become necessary to design prefabricated HV switchboards capable of withstanding an internal arc, without affecting the safety of personnel in the

proximity of the switchboard, either due to burns or ejection of switchboard components.

The design of such special switchboards involves real power tests, followed by simulation using computer programs.

The process of evolution of an originating in an enclosed volume equipped with the required pressure relief valves involves complex phenomena during the following phases :

- **compression phase** (5 to 15 ms), during which the pressure rises between 1.2 and 1.8 bars,

- **the expansion phase** (about 10 ms), followed by opening of the pressure relief flaps, and coinciding with a pressure drop,

- **the emission phase** (200 to 300 ms), during which hot gases are quasistabilized mode evacuated.

- **thermal phase** (200 ms, up to several seconds), during which the arc burns plating and insulators up to perforation. For example, 4 mm plating is punctured by a 35 kA arc in 300 ms.

Verification of the internal arc behaviour was first of all classified by a PEHLA (German test organization) directive, and, since 1978, by modification No. 2 of CEI 298, subsequent to the work of subcommittee 17C.

opto-electronic detection

A noticeable reduction in the destructive effects of arcs can be obtained by reducing their duration below the conventional limit of one second; this limit corresponds to an often long time for protection device to act, for selectivity requirements. This reduction in arc duration is rendered possible by installing opto-electronic detectors, which cause the master circuit-breaker (input or coupling) to open in less than 100 ms. The thermal phase is practically nonexistent, resulting in a notable reduction in damage, with a rapid return to normal service.

bibliography

- (1) A. Hochrainer
Movement of short-circuit arcs in high voltage installations.
ETZ A Bd 77 11/5/56.
- (2) E. Eidinger and W. Rieder
Behaviour of arcs in transverse magnetic fields.
Archiv. F. elect. BD 43 1957
- (3) L. Muller
Propagation of short high current arcs.
Electrizitätsw. H8 4/58.
- (4) L. Fechant
Speed of movement of arcs in air.
REG 9-59
- (5) L. Chaineaux and C. Gagnières
Puncturing of cabinets by arcs.
Revue industr. ; minérale 5/62.
- (6) G. Bouvier
Incidents occurring on electrical installations aboard ships.
ATMA 1971.
- (7) A. Ducluzaux
Electrodynamic forces.
Cahier tech. MG n° 7 2/76.
- (8) R. Calvas and F. Sautriau
Protection of networks by logic selectivity systems.
Cahier tech. MG n° 2 1/78.
- (9) P. Schueller
Low voltage breaking by current limiting.
Cahier tech. MG n° 103 6/80.
- (10) C. Albertin
Compact limiter circuit-breakers, towards unlimited break capability.
Cahier tech. MG n° 111 6/81.

Georges Bouvier

IEG engineer, started working at Merlin Gerin in 1948 after working as a technical education professor.

Since then, he has directed the high power test laboratory, the low voltage technical services and the low voltage equipment research. His work resulted in the first DMG selective circuit-breaker used in the French Navy, together with the first limiter circuit-breakers (in 1954) capable of breaking 100,000 A rms at low voltage.

Mr. Bouvier retired from professional activity in 1970.

André Ducluzaux

ESME graduate engineer in 1950, science graduate in 1951, started working with Etablissements Merlin Gerin in 1952.

Initially, Monsieur Ducluzaux participated in prefabricated LV switch-board design, then in the perfection of power test station equipment.

In 1960, as head of the design office for high current LV circuit-breakers, he developed the DA circuit-breakers, and was then responsible for LV research. In 1969, he became project manager for the general research department.

In this capacity, he developed a new, ultra high-speed circuit-breaker design for very high current limiters, based on the Thomson effect.