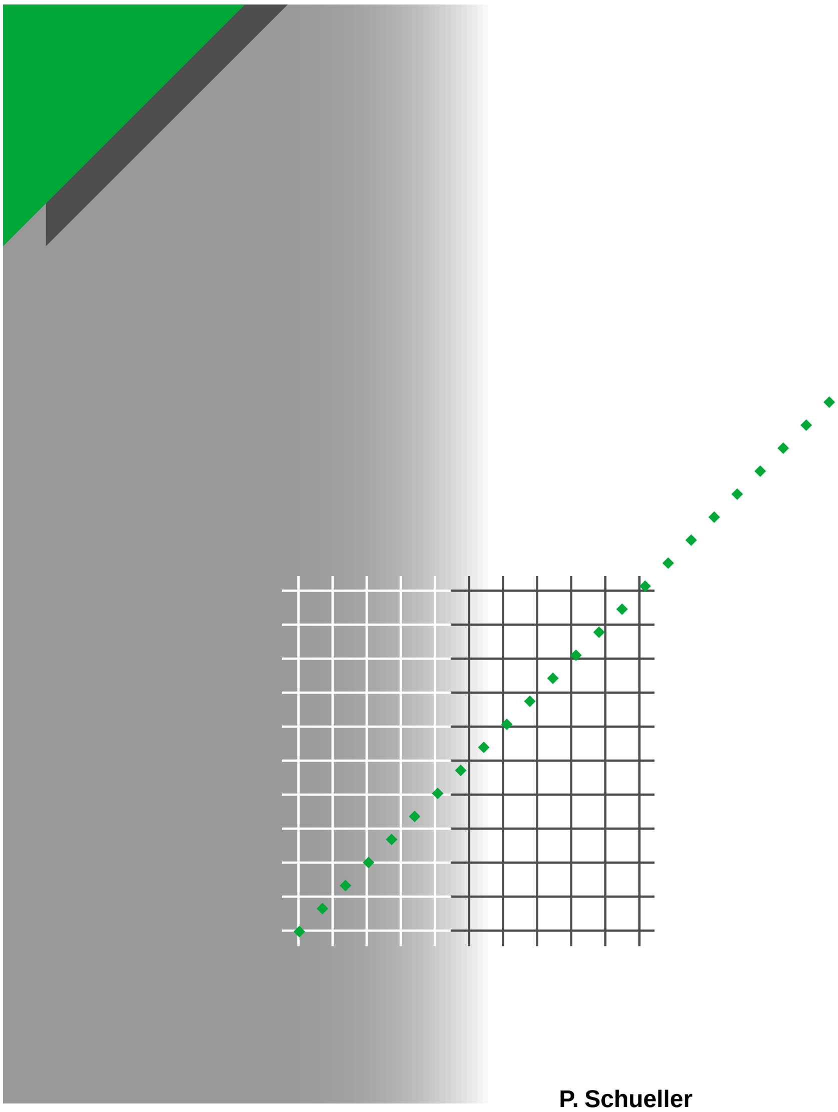
Collection Technique

Cahier technique no. 163

LV breaking by current limitation



P. Schueller

Merlin Gerin
Modicon
Square D
Telemecanique

Schneider Electric

"Cahiers Techniques" is a collection of documents intended for engineers and technicians, people in the industry who are looking for more in-depth information in order to complement that given in product catalogues.

Furthermore, these "Cahiers Techniques" are often considered as helpful "tools" for training courses.
They provide knowledge on new technical and technological developments in the electrotechnical field and electronics. They also provide better understanding of various phenomena observed in electrical installations, systems and equipments.
Each "Cahier Technique" provides an in-depth study of a precise subject in the fields of electrical networks, protection devices, monitoring and control and industrial automation systems.

The latest publications can be downloaded from the Schneider Electric internet web site.
Code: **http://www.schneider-electric.com**
Section: **Experts' place**

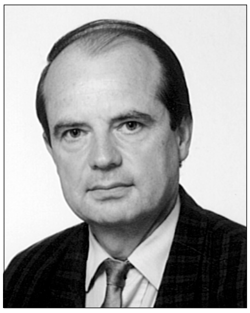
Please contact your Schneider Electric representative if you want either a "Cahier Technique" or the list of available titles.

The "Cahiers Techniques" collection is part of the Schneider Electric's "Collection technique".

Foreword

n° 163

LV breaking by current limitation



Pierre Schueller

Arts et Métiers engineer and graduate from the Grenoble Electrotechnical Institute, he joined Merlin Gerin in 1967. His first function consisted in design of low voltage limiting circuit-breakers for terminal and then industrial distribution.
At the Technical Section of the Low Voltage Power Division, he was responsible of the engineering and design department for sensor and actuator development, from 1983 to 1996.
He has since been dealing with standards and patents for the account of Low Voltage Equipment and Systems Division.

ECT 163(e) first issue september 1998

LV breaking by current limitation

This “Cahier Technique” provides a simple introduction to the principles of low voltage current limitation, a technique developed by Merlin Gerin in direct current as early as 1930 and in alternating current in 1954.
It simplifies understanding of the advantages gained by using limiting circuit-breakers in electrical installations.
The document ends with a detailed bibliography for those wishing to satisfy their scientific curiosity.

Content

1 General

1.1 Definition

A device is said to be limiting when the current passing through it during a short-circuit has an amplitude considerably lower than the prospective current (see **fig. 1**).

In the case of limiting circuit-breakers, this reduction in amplitude is accompanied by a reduction in the current flow time T compared with the short-circuit current flow time of a non-limiting circuit-breaker.

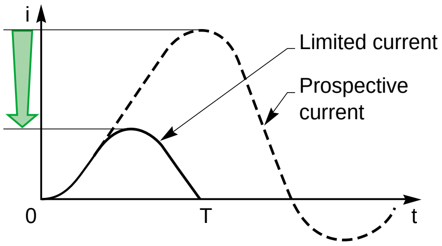


***Fig. 1**: representation of prospective and limited short-circuit currents.*

2.1 Why limit?

- To make more cost effective circuit-breakers, especially in low rated current ranges. Only the limited current, far smaller than the prospective current, flows through the limiting device, which then has only to break this limited current.
- To minimise fault current effects in electrical installations.

What are these effects?

Electromagnetic effect

At a distance d from a conductor through which a current of strength I flows, a magnetic induction B is in the air with a value:

$$B = 2 \times 10^{-7} \frac{I}{d} \text{ (in MKSA units)}$$

Example: where I = 50 kA and d = 10 cm,
B = 0.1 tesla.

Possible consequence: disturbance of electronic devices placed close to electric conductors through which a short-circuit flows.

Mechanical effects

- If at the distance d of a conductor through which a current I flows, there is another conductor parallel to the first with the same length L and through which a current I' flows, this conductor is subjected to a force F (attraction if the direction of I and I' is identical, repulsion if it is not) which equals per unit of length:

$$\frac{F}{L} = B I'$$

If the same current I flows through both conductors, the formula becomes:

$$\frac{F}{L} = 2 \times 10^{-7} \frac{I^2}{d} \text{(in MKSA units).}$$

Example: where I = 50 kA and d = 10 cm,

$$\frac{F}{L} = 5000 \text{N/m}$$

Possible consequence: deformation or rupture of parts.

- In all switchgear, separable contacts, held together by springs, tend to open under the effect of an electrodynamic force known as repulsion. These forces must sometimes be balanced by “compensation” systems.

For I = 50 kA, this force is 1000 N.

Possible consequence: arcing between control device contacts with damage to contacts.

Thermal effect

During a short-circuit, there is an adiabatic temperature rise $\Delta\theta$ of the S cross-section conductors, of up to:

$$\Delta\theta = \frac{k}{S^2} \int_T i^2 \, dt$$

- $\int_T i^2\,dt$ is known as the thermal stress (given in $A^2\,s$).
- K is a coefficient dependent on the type of conductors (approximately $6 \times 10^{-3} \frac{°K\,mm^4}{A^2\,s}$ for copper).

Example: A copper wire with a cross-section of 1.5 mm^2, is heated to roughly 110°K when a current period of 2000 A r.m.s. at 50 Hz flows through it.
Obvious possible consequences: deformation of device and destruction of insulating material with risks of fire and electrocution.

1.3 How to limit?

Take a single-phase AC circuit with an apparent power S and voltage E, delivering in a load Z through a protective device A presenting a negligible impedance before it is activated (see **fig. 2**), with for the group:

source + line + fault
R = equivalent resistance
L = equivalent inductance.

When a short-circuit occurs at the terminals of load Z, before A is activated (thus with negligible u_a) the mains is supplied with an electromotive voltage e such that:

$$e = Ri + L\frac{di}{dt}$$

the current is thus established with an initial derivative equal to:

$$\left(\frac{di}{dt}\right)_0 = \frac{e}{L}$$

This derivative is greatest for short-circuits occurring when mains voltage is highest. For power factors less than 0.25, this corresponds to a virtually symmetrical prospective current.
Example: a 400 V 50 Hz three-phase source, phase-to-phase, with an apparent power S = 3200 kVA and a maximum short-circuit current of 100 kA r.m.s. (with a peak which can exceed 200 kA in asymmetrical condition).
The maximum initial current derivative is 44 kA/ms.

To prevent such currents developing and to guard against their effects, a limiting protective device A must be placed in the circuit. When a short-circuit occurs, this device quickly provokes a voltage drop or back electromotive voltage u_a which opposes current increase.

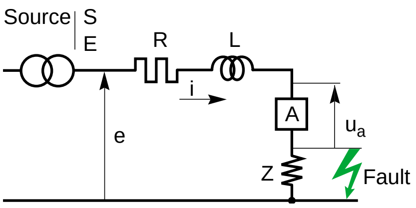


Fig. 2: schematic diagram of a faulty circuit.

1.4 Conditions to be respected by u_a for current limitation

The equivalent single-phase diagram yields the following relation for a full short-circuit:

$$E = Ri + L\frac{di}{dt} + u_a$$

A vectorial representation of the equivalent impedance for power factors cos φ ⩽ 0.25 (thus φ > 75°) shows that the term L di/dt is far larger than the term R i (see **fig. 3**). Thus if the latter is not taken into account:

$$e = L\frac{di}{dt} + u_a$$

then the limited current reaches its peak value, i.e. when

$\frac{di}{dt} = 0$, the electromotive voltage has the value u_a.

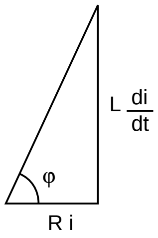


Fig. 3: vectorial representation of the two components R i and L di/dt.

We can thus conclude:
the highest limited current is reached when voltage u_a equals source voltage e (see **fig. 4**).

One of the first consequences is current limitation, which is easiest to obtain when mains voltage e is low.

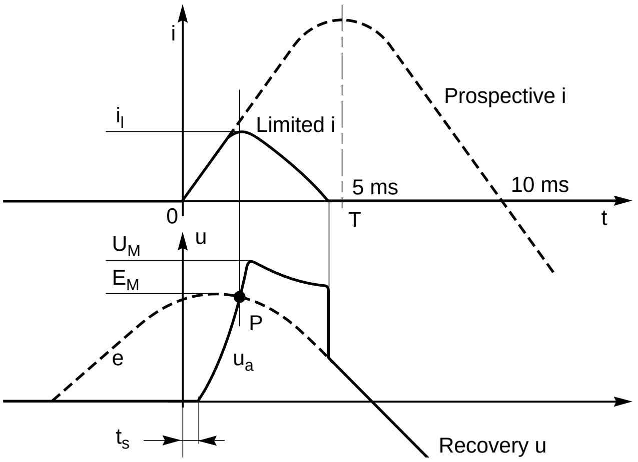
Then, in **figure 4** where P is the point of intersection of the development curves of voltage u_a and voltage e of the source, the curves show that to obtain correct limitation, the instant of intersection P must occur well before the highest prospective current (thus < 5 ms in 50 Hz).
It is thus advantageous for voltage u_a to develop as quickly as possible.

Finally, in order to reduce short-circuit current the maximum voltage U_M introduced by u_a must be greater than the maximum voltage E_M of the source.

In short, the three conditions to be respected by u_a for correct limitation are:

- **early action** ⇒ ts minimum. However there is a lower limit laid down by the device activation threshold (e.g. maximum setting of a circuit-breaker's instantaneous trip units or non-melting thermal stress for fuses),
- **prompt action** ⇒ rapid development of voltage u_a achieved for example in a circuit-breaker by high contact acceleration,
- **high action** ⇒ $U_M > E_M$ obtained for example by elongation, splitting and cooling the arc in the breaking device.

Out of these three conditions, the first two, rapidity and speed, are the most important. As regards the third condition, U_M need not overshoot E_M by a large amount. Consequently, for a three-phase 420 V r.m.s. network (thus with a peak voltage of $240\sqrt{2}=340$ V), a U_M voltage of 400 V is sufficient.



Note: t_s is the moment of appearance of voltage u_a (e.g. contact separation or vaporisation of a fuse link).

Fig. 4*: curves u = f(t) and i = f(t) development of arcing voltage and its consequence: decrease in short-circuit current.*

1.5 Special case of miniature circuit-breakers

In this case, the short-circuit power factors are normally greater than 0.5 The term Ri can no longer be ignored. Thus, when a limited current reaches its highest value, the following can be written:
$u_a = E_M - R\,I_l$
which shows that maximum voltage u_a can remain less than maximum mains voltage.

For example: on a circuit with a phase to neutral voltage V = 240 V r.m.s. (i.e. $E_M = 340$ V) if the prospective short-circuit current Ip is 6 kA with cos φ = 0.6, knowing that R = V / Ip cos φ and assuming a limited peak current I_l of 4 kA, the calculation yields:
$u_a = 243$ V, less by nearly 100 V to E_M.
As regards the three conditions to be met for correct limitation, the next two chapters look into the various physical principles and techniques implemented in the design of limiting devices, fuses and circuit-breakers.

2 How to obtain voltage u_a

A prompt voltage drop u_a is generally obtained by inserting a number of devices in series in the circuit.
However, it should be pointed out that limiting devices do not always have a breaking function and must then be backed-up by a circuit-breaker when used for protection of electric circuits.

2.1 Status change resistor

Its creation is based on two principles:

- melting a solid conductive element in an impervious enclosure by overshooting the thermal melting stress. This is the traditional fuse with the disadvantage that the fuse link has to be replaced after use;
- in the above case replace the fuse link by a substance easily vaporisable on a high thermal stress (e.g. sodium or potassium), but whose vapours, subjected to high pressure, quickly recondense after the breaking arc has extinguished: this is the self-regenerating fuse.

Note that this fuse type is always backed-up by a parallel resistor to prevent overvoltage.
Moreover, a circuit-breaker must also be placed in series (with the fuse and its resistor) to break the circuit before regeneration of the fuse link.

2.2 Positive temperature coefficient resistor (but with a limited temperature rise to remain below melting point).

Permanently installed resistor

In practice its use is restricted to rated currents under 100 A for continuous heating purposes.

Parallel-connected resistor, with contacts opening quickly on a fault [1] [2]

Without the continuous heating stress on the resistor, this system enables higher rated currents to be reached. However, constraints due to current commutation from parallel contact to PTC resistor are still present.

Moreover, other contacts must always be connected in series to break the limited current.

2.3 Variable resistor formed by the actual breaking arc

The breaking arc in a circuit-breaker is in fact a variable resistor with a value which can be increased by cooling. Use of a sufficiently energetic cooling means ensures the required voltage is reached for current limitation.

On limitation resistors, the arc has the added advantage of not generating overvoltages proportional to the current. Whatever the breaking conditions, maximum arcing voltage remains at a virtually constant and controllable value.

Furthermore, arc insertion is automatic on separation of two metal contacts through which a high current flows.

In practice, in networks of over 1000 V, it is hard to obtain sufficient arcing voltages in small volumes to limit the current (except for low rated current fuses used in HV up to 36 kV).

This explains why use of the arc as a limitation resistor is the most common and cost effective process in LV network protection.

All these means favour the creation of u_a, thus meeting the need to “aim high”. However prompt and early action are also necessary (refer to previous chapter). Hence the advantage of contact propellents and ultra-fast trip units for the limiting circuit-breakers presented in the next chapter.

3 Contact propellents and ultra-fast trip units

3.1 Contact propellents

The main systems proposed for contact separation (thus arc insertion) are classified according to the origin of the energy required for them to work.

Short-circuit current independent systems

With an auxiliary energy source which may be:

- Mechanical
  - energy stored in a spring,
  - pneumatic energy,
  - hydraulic energy.

Correct limitation requires accelerations several thousand times the acceleration of gravity, to be obtained in very short times (approx. 1 ms). In practice, these three energy sources cannot reach this objective in acceptable economic conditions.

- Chemical

The chemical energy contained in explosives is able to develop the required accelerations, but its use remains complex. Moreover, the explosive cartridge must be replaced after use. This process has not therefore really been developed **[5] [13]**.

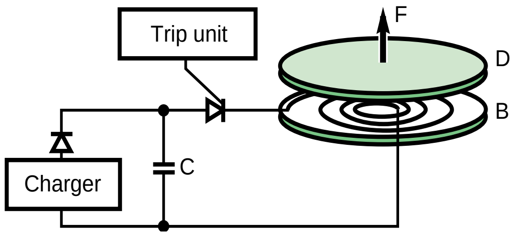


Fig. 5: diagram showing a contact propellent according to Elihu Thomson's principle.

- Electrical

The necessary energy is stored in a capacitor.

This principle is the result of the experiment conducted at the end of the 19th century by Elihu Thomson (see **fig. 5**).

A flat coil B wound in a spiral is magnetically coupled as near as possible with conductive disk D. The sudden discharge of capacitor C in coil B, controlled by an electronic trip unit, creates induced concentric currents of opposite direction in disk D. The result is a repulsion force F on the disk which is both very high and very fast (less than a millisecond after the tripping order), but short (only a few ms).
This process is sometimes used to quickly unlatch limiting circuit-breakers **[6] [8]**.

Current-operated devices

The energy required to propel the moving contact is taken off the actual fault current.

A great number of devices use this principle.

These systems are divided into two major families, depending on whether or not magnetic circuits are used (saturable).

- Electrodynamic

(without magnetic circuit, thus not saturable).

Natural contact repulsion under the effect of electrodynamic forces is amplified by special configurations, two examples of which are given below:

- repulsion between two conductors forming a loop: a fixed one A and a moving one B, rotating around point O (see **fig. 6a**).
- repulsion on a moving contact in bridge B accentuated by crossing of the fixed contacts A and A' (see **fig. 6b**).

a) Simple repulsion

b) Reinforced repulsion

Fig. 6: diagram showing contact propellents with self-energized electrodynamic current.

■ Electromagnetic

With a magnetic circuit and thus with occurrence of the saturation phenomenon.

☐ **Figure 7a** shows this device: the solenoid S through which a high (short-circuit) current flows, swallows the moving magnetic core N which strikes the moving contact B thus causing the circuit to open.

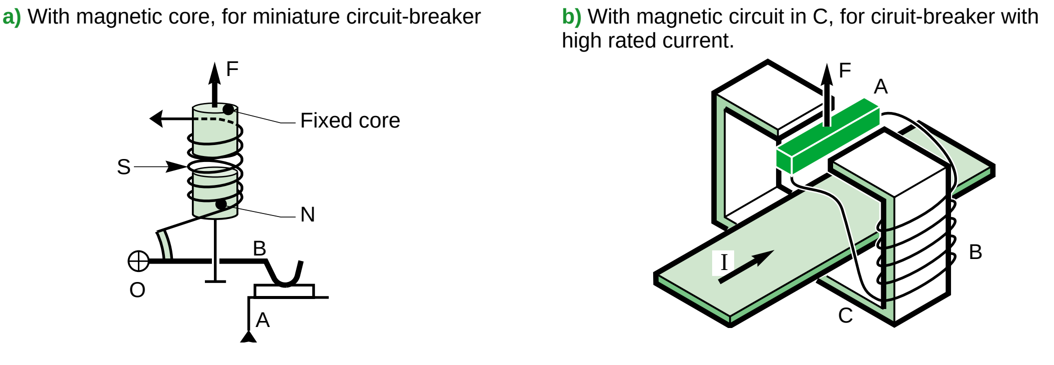
This is the standard diagram for miniature circuit-breakers **[10]**.

☐ **Figure 7b** shows how this principle is used for devices with a high rated current.
The device now consists of a magnetic circuit C, with airgap, through which current I of the circuit to protect flows.
A coil B around the magnetic circuit, closes on a bar A placed in the circuit airgap. A and B form the secondary winding of an airgapped current transformer with I as the primary current.
Interaction of the secondary current in A and of the magnetic field in the airgap generates a force F which propels a moving contact.

This device has been used for limiters installed on DC electrical traction networks **[1]**.

Remark

Whereas the energy available with an auxiliary source system is separate from the fault current level, the force developed by current-operated devices and its moment of activation are automatically linked to the value of this fault current. This propellent type therefore has a current level below which the system no longer works: contacts are then separated simply by the device's operating mechanism.


a) With magnetic core, for miniature circuit-breaker

b) With magnetic circuit in C, for ciruit-breaker with high rated current.

***Fig. 7**: diagrams showing self-energized electromagnetic contact propellents.*

3.2 Ultra-fast trip units

Their function is to mechanically confirm contact “reflex” separation. Their presence is vital when the contact propellent is self-energized and the moving contact does not latch in the open position.

In actual fact, given the mechanical inertia of the moving contact, contact separation must be relieved in less than 10 ms by the opening mechanism, since the repulsion force is lost after the short-circuit current is broken. Otherwise, the pressure springs close the contacts and restore the short-circuit.
These devices use the same electrical, electrodynamic and electromagnetic principles described in the above paragraph.

Thus, to give an example, in some miniature circuit-breakers, the moving magnetic core (N in the diagram in **figure 7a**) is used not only to accelerate contact separation, but also to quickly unlatch the mechanism holding the moving contacts in the closed position. Likewise, the principle shown in **figure 5** has already been used for this unlatching function **[6]** **[8]**.

Other ultra-fast trip units use the pressure developed by the electric arc in the arc chute when breaking a high current.

As an arc moves through an arc chute, it builds up a pressure of several bars which becomes available as soon as the limited current reaches its highest value (at point P in **figure 4**).

The use of this principle, patented by Merlin Gerin, enables the construction of ultra-fast and highly limiting circuit-breakers: via appropriate ducts and valves, this pressure is used to actuate a piston which controls in less than 5 ms the circuit-breaker opening mechanism.

4 Conclusion

You will now have realised the importance of research in the creation of high performance circuit-breaker ranges.

Since 1930, Merlin Gerin, along with other manufacturers, has helped increase safety and reliability of electrical power distribution. Recent patents filed show the promising future of limiting circuit-breakers in electrical power distribution, with their capacity to increase its discrimination and hence availability.

5 Bibliography

[1] Disjoncteurs ultra-rapides pour courant continu.
P. BRANCHU.
Patents n° 596.483 (1925) - 629.040 (1927) - 721.451 (1931).

[2] Nouvelle disposition de branchement pour limiteurs de courant.
K. KESL.
RGE, february 1942, p. 85-96.

[3] Coupure des courants de l'ordre de 100 kA en BT.
G. BOUVIER.
RGE, november 1955, p. 554.

[4] Disjoncteurs limiteurs à basse tension pour courants alternatifs.
A. MOLAS.
RGE, may 1958, p. 259-276.

[5] Problèmes de coupure et utilisation des limiteurs Is.
P. BRUCKNER.
ETZ-B, H3, march 21st 1959.

[6] Disjoncteurs rapides avec limitation du courant.
A. ERK.
ETZ-B, H7, april 2nd 1962, p. 169.

[7] L'accroissement des courants de court-circuit et leur maîtrise dans les installations BT.
P. BRUCKNER.
ETZ-B, H19, september 17th 1962, p. 511.

[8] Limitation et coupure du courant avec un disjoncteur Gearapid dans un réseau alternatif.
H. FEHLING.
ETZ-B, H19, september 17th 1962, p. 537.

[9] Disjoncteur à limiteurs de courant.
E.B. HEFT.
Power, july 1968, p. 55.

[10] Exploitation de la limitation des courants de court-circuit.
J.R. COCHENNEC.
Revue Klöckner-Moeller, november 1970.

[11] Interrupteurs limiteurs du courant de court-circuit.
G. CANTARELLA.
L'Elettrotecnica, july 1970.

[12] Développement de disjoncteurs sans fusibles à limitation de courant.
H. SUZUKI.
Revue Hitachi, vol. 19, n°12, p. 441.

[13] Le système «Pyristor» de Ferraz.
G. GUEZ.
Moniteur de l'Electricité, october 1984, p. 42.

Schneider Electric

Direction Scientifique et Technique,
Service Communication Technique
F-38050 Grenoble cedex 9
Fax: 33 (0)4 76 57 98 60

DTP: Sodipe - Valence
Edition: Schneider Electric
Printing: Imprimerie du Pont de Claix - Claix - France - 1000
- 100 FF -