n° 114

residual current devices

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Through his work in the fields of protection of persons and low voltage installations, he has acquired valuable know-how regarding residual current devices used to provide earth fault protection.**

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residual current devices

"The earth leakage circuit-breaker is generally recognized (throughout the industrialized world) as the best and most reliable of the protective devices which have been developed to offer protection against indirect contact in the low voltage field".
Extract from the lecture given to the 5th International Conference of the AISS (Lucerne, 1978), by professor C.F. DALZIEL (Berkeley, USA), one of the pioneers of research into the effects of electricity on man.

contents

1. Reminders	Some definitions	p. 4
	Earth leakage protection and differential protection	p. 4
2. Patho-physiological effects of electricity on people	Effects as a function of current magnitude	p. 5
	Effects as a function of exposure time	p. 6
3. Types of protection provided by the RCDs	Protection of persons	p. 7
	Fire protection	p. 7
	Protection of electrical equipment and circuits	p. 7
4. Principle of operation of the RCDs	Detectors	p. 8
	Measuring relays	p. 10
5. Different types of RCD technology	Production standards	p. 12
	Earth leakage socket and earth leakage extension	p. 12
	Earth leakage load switch and earth leakage circuit-breaker < 100 A	p. 12
	Industrial earth leakage circuit-breaker 100 to 630 A	p. 13
	Earth leakage relays	p. 13
6. Coordination of protection	"Vertical" discrimination	p. 14
	"Lateral" discrimination	p. 15
	HV discrimination	p. 15
7. Special cases of direct current and mixed systems	Fewer risks for people	p. 17
	RCD standards	p. 17
	Real fault currents	p. 17
	Direct current return	p. 20
	Technological solutions	p. 21
8. Conclusion		p. 22
9. Appendix	RCD and EMC	p. 23
10. Bibliography		p. 24

1. reminders

some definitions

Live conductors
Conductors used for the transmission of electricity, including the neutral on a.c. systems and the compensator on d.c. systems.

Mass
Conductive part liable to be touched and normally insulated from the live parts but capable of being accidentally energized at a dangerous voltage.

Fault current Id
Current resulting from an insulation fault.

Residual earth leakage current
RMS value of the vectorial sum of the currents flowing through all the live conductors of a circuit, at a point in the electrical installation:
IΔn on low voltage, Ih on high voltage (or I⏚).

Residual earth leakage operating current: If
Value of the residual earth leakage current causing the operation of an earth leakage device.
According to standards for construction of low voltage earth leakage devices it is necessary, for the threshold IΔn, to have at 20° C:

$$\frac{I\Delta n}{2} < If < I\Delta n$$

At high voltage, the zero phase sequence relays have an operating current equal to the setting threshold in amps within their accuracy limits.

Residual current device (RCD)
Device whose main operation principle is the residual earth leakage current.

Direct contact
Contact between persons and the live parts of electrical equipment (conductors and normally live parts).

Indirect contact
Contact between persons and exposed conductive parts which are accidentally made live (generally as a result of an insulation fault).

earth leakage protection and differential protection

A residual current device (RCD) incorporates a measuring device, connected with a toroid around the live conductors, which detects a difference, or more precisely a residual current, (see fig. 1).
The existence of a residual earth leakage current means that there is an insulation fault between a live conductor and a frame or earth.
This current takes an abnormal path, generally earth, back to the source. The residual current device includes a circuit-opening function (load switch, contactor, circuit-breaker) which automatically disconnects the faulty circuit.

Differential protection consists of one or more measuring devices whose function is to detect a difference between the input and output current on part of the installation: e.g., a line, a cable, a transformer, or a generator set.
This protection is used on medium and high voltage systems. Differential protections are used for protection against insulation faults (see fig. 2), or to protect against faults between phases (see fig. 3).
There is thus a clear distinction between residual current devices and differential protection. This article deals with residual current devices (RCD).

The three earthing systems
Three types of earthing systems are officially recognized by the IEC 364-3, and they are used in different ways in different countries (see fig. 4).
The residual current device is used either for the protection of persons (indirect contact in TT systems, direct contact as a back-up measure, whatever the earthing system) or for the protection of equipment.

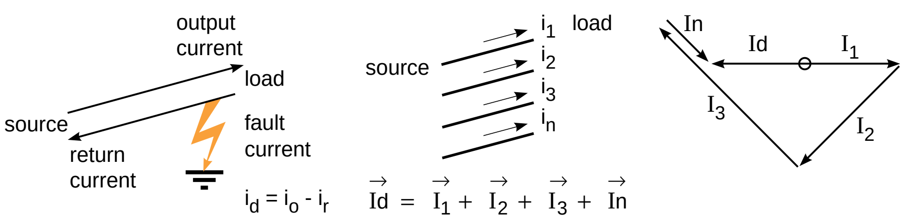


fig. 1: a current leak results in an earth leakage fault current: i_a.

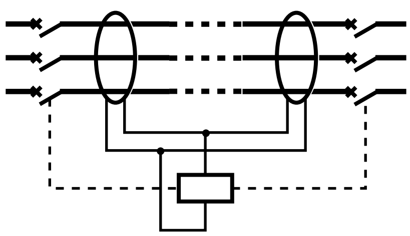


fig. 2: differential protection against insulation fault inside a cable.

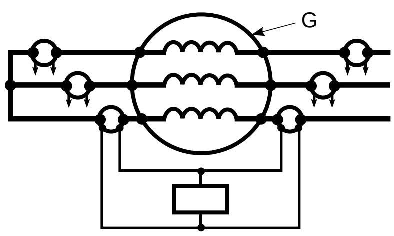
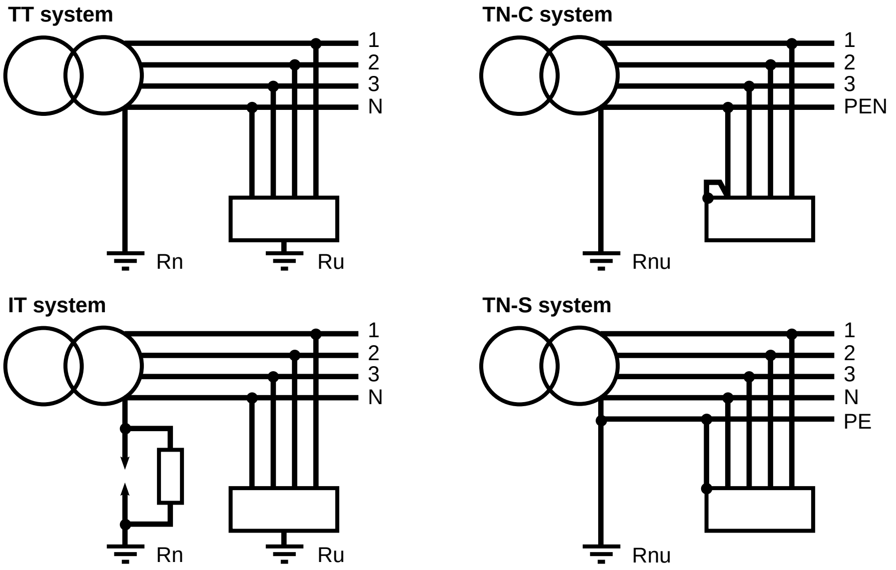


fig. 3: differential protection against fault between phases inside a generator.



The first letter indicates whether the neutral at the origin of the installation is earthed or unearthed.
The second letter indicates to what the earth and neutral frames are connected.

fig. 4: earthing system diagrams.

2. patho-physiological effects of electricity on people

Since residual current devices are used mainly for the protection of personnel, it is essential to be fully aware of the sensitivity thresholds of human beings to electric current, and of the risks involved, in order to be able to use these devices correctly.
The International Electrotechnical Co-mission (IEC) has made a detailed study of this problèm in order to standardize viewpoints throughout the world. Many scientists (Dalziell, Kisslev, Osypka, Biegelmeier, Lee, Koeppen, Tolazzi, etc...) have assisted with this work, and have helped to clarify the subject.

effects as a function of current magnitude

The effects of electricity passing through the human body depend upon the person's weight. Numerous tests have shown that, on average, currents giving a specific effect have a relative value of:

- 100 for women;
- 150 for men;
- 50 for children.

Thus the effect of current on women (the human average) depends on the magnitude of this current (see fig. 5).

effects (for t < 10 sec)	**current (mA)** direct current	**alternating current** 50/60 Hz	10 kHz
slight tingling, perception threshold	3.5	0.5	8
painful shock but no loss of muscular control	41	6	37
non-release threshold (I_L)	51	10	50
considerable breathing difficulty	60	15	61
respiratory paralysis threshold		30	

fig. 5: effects of low electric currents on people.

effects as a function of exposure time

The risk of: non release, respiratory arrest or irreversible cardiac fibrillation (1) increase in proportion to the time during which the human body is exposed to the electrical current (see fig. 6).

Safety voltage (U_L)

According to environmental conditions, in particular whether or not water is present, standard NF C 15-100 stipulates a safety voltage, for a.c. current, of:

- 50 V for dry or damp atmospheres;
- 25 V for wet atmospheres,

e.g. outside sites.

Direct contact

Not dangerous for contact voltages corresponding to the safety voltages indicated above.

If voltage exceeds U_L, the fault current flowing through the person can be detected by an earth leakage device. Table 1 (cf. fig. 5) shows that its operating threshold is ≤ 30 mA. Moreover, its operation must be instantaneous since fault current value cannot be estimated beforehand.

Indirect contact

The danger threshold is also set by the safety voltage U_L. Contact voltage must be less than U_L to ensure there is no risk when mains voltage exceeds U_L. For example in earthed neutral conditions, this means choosing an earth leakage operating threshold ($I\Delta n$) such that:

$$I\Delta n \leq \frac{U_L}{Ru}.$$

The operating time of the protection must be chosen as a function of the curves (see fig. 6) and of the contact voltage (see fig. 7).

A genuine risk is seen to exist to the right of curve b in:

- **zone 3**

Normally no organic damage. Likelihood of muscular contractions and breathing difficulties, of reversible disturbances in the formation and propagation of pulses in the heart, including ventricular fibrillation and temporary cardiac arrest without ventricular fibrillation, increasing with current magnitude and time;

- **zone 4**

In addition to the effects of zone 3, the likelihood of ventricular fibrillation is:

- □ roughly 5 %, for curve c_2,
- □ more than 50 % beyond curve c_3.

Patho-physiological effects such as: cardiac arrest, respiratory arrest, serious burns, increase in proportion to current magnitude and exposure time.

The operating times recommended by the standard for Residual Current Devices as a function of contact voltage are given in the tables in figure 7.

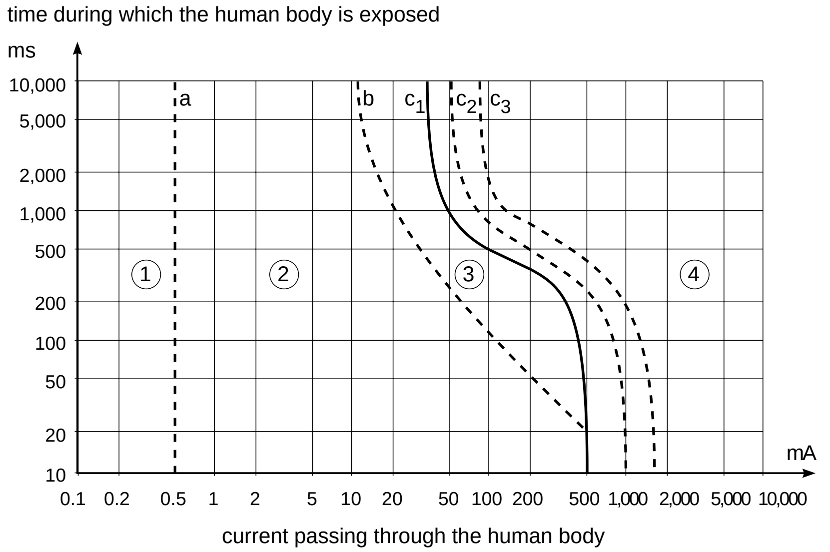


fig. 6: time/current zones of a.c. current effects (15 Hz to 100 Hz) on people as in IEC 479-1.

■ dry or damp atmospheres or sites: $U_L \leq 50$ V

presumed contact voltage (V)	maximum breaking time of protection device (s)	
	a.c. current	d.c. current
< 50	5	5
50	5	5
75	0.60	5
90	0.45	5
120	0.34	5
150	0.27	1
220	0.17	0.40
280	0.12	0.30
350	0.08	0.20
500	0.04	0.10

■ wet atmospheres or sites: $U_L \leq 25$ V

presumed contact voltage (V)	maximum breaking time of protection device (s)	
	a.c. current (a)	d.c. current (b)
25	5	5
50	0.48	5
75	0.30	2
90	0.25	0.80
110	0.18	0.50
150	0.10	0.25
220	0.05	0.06
280	0.02	0.02

fig. 7: maximum holding time of contact voltage.

(1) Cardiac fibrillation is a loss of synchronism in the action of the walls of the heart (distolic and systolic), through the effect of the periodic excitation due to the alternating current, and causes the blood circulation to stop.

3. types of protection provided by the RCDs

One function of RCDs is to measure the leakage currents of electrical conductors; in this way they monitor the insulation of the system and the load.
Leakage currents constitute a danger to both persons and equipment.
This danger is greatly influenced by the choice of earthing system and can be considerably reduced, under normal working conditions, by the basic precautions specified in installations standards:

- spacing and covers;
- insulation - class II equipment - safety transformers;
- earthing;
- equipotential bonding.

protection of persons

Direct contact

The full leakage current is experienced by the person in contact with the live component, who is thus exposed to the patho-physiological risks already described.
An RCD on the line side of the point of contact measures the current passing through the person and interrupts the current.
The risks involved and the regulations require the use of high or very high sensitivity RCDs (30, 10, or even 6 mA) when the risk is based on the installation environment or the persons.
The risk is independent of the earthing system.
If there is a breaking risk or if there is no protection conductor, the use of a high sensitivity RCD is necessary. This is the case in France where para. 532-2.6.1. of standard NF C 15-100 stipulates for sockets: “RCDs with a threshold no greater than 30 mA must protect the circuits supplying sockets”:

- □ all sockets in the case of wet atmospheres or temporary installations,
- □ sockets of rating ≤ 32 A in all other installation cases».

Most countries, even the USA and Germany, which have LV distribution with an earthing system, have similar practices.

Indirect contact

The leakage current depends upon the fault resistance and the earthing system. It returns to source via the protection conductor and/or via earth.
The person is exposed to the voltage developed in the return circuit taken by the fault current: Ud; or more accurately to the voltage at the point of contact, which may be lower if equipotential bonding is involved.

Where both a TN and an IT system are involved (dual fault), the protection is normally provided by overcurrent protection (calculation/ measurement of the loop impedances). If the impedance is too great (long distance cables), the solution lies in using a low sensitivity RCD (1 to 30 A).

In the case of the TT system
(see fig. 8)
The protection must be provided by using medium or low sensitivity RCDs whose operating threshold depends upon the safety voltage

$$I\Delta n \le \frac{U_L}{Ru}.$$

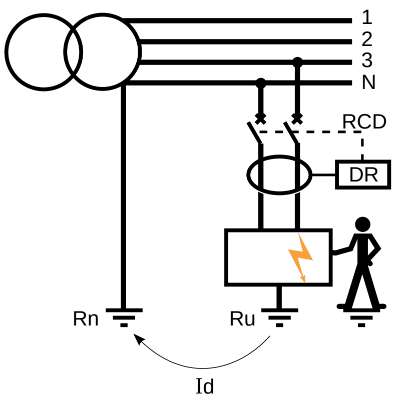
fire protection

It is recognised that a 300 mA current can bring two metal parts in pinpoint contact with each other to incandescence.
Whatever the earthing system, electrical installations in fire risk premises are equipped with RCDs of sensitivity: $I\Delta n \le 500$ mA.
(in France, in agriculture alone, about 150 fires per day were reported in 1977, of which 40 were of electrical origin).

protection of electrical equipment and circuits

Using the connecting to neutral system(or the unearthed neutral for the second fault), insulation faults are eliminated by overcurrent protection devices. Considerable damage may result, which can be greatly limited by the use of a low sensitivity RCD (10 A for example).

Example:
A lamination in the magnetic circuit of a motor breaks down, which thus has to be changed instead of rewound.
The higher the operating voltage, the greater must be the protection, since the energy dissipated at the fault point is proportional to the square of the voltage. On medium and high voltage, this risk plays a large part in the choice of earthing system.
Finally, at low voltage whatever the earthing system, RCDs can provide a useful indication of the degree of deterioration of the insulation.



$$Id = \frac{U}{Rn + Ru} \qquad Uc = Ru \;\; Id$$

fig. 8: contact voltage generation principle in TT.

4. principle of operation of the RCDs

Residual current devices consist of at least two component parts:

The detector
This must be capable of providing an electrical signal when the sum of the currents circulating in the live conductors is other than zero; this difference can be considered as arithmetical if the wiring system under surveillance is carrying direct current and vectorial if the system is carrying alternating current.

The measuring relay
This compares the electrical signal supplied by the detector against a reference value, and causes the associated switching device to open. This being after an intentional time-delay if applicable.

detectors

Toroid
With alternating current, the type of detector most frequently used is a toroidal current transformer or “toroid”. This surrounds all the live conductors and is thus excited by the residual magnetic field corresponding to the vectorial sum of the currents passing through the phases and neutral.
The induction in the transformer and thus the electrical signal available on the secondary is theoretically the image of residual earth leakage current.
In fact, in order to ensure that the "response" of the toroid is both consistent and linear, a number of precautions must be taken:

The live conductors passing through the toroid must be placed as close as possible to the centre of the ring to ensure that their magnetic effect is nulled in the absence of residual current.
The magnetic field developed by a conductor decreases in proportion to distance; the magnetic field is thus very large at point A (see fig. 9), this produces a local magnetic saturation and the effect of phase 3 is no longer proportional. At high currents, the appearance of stray residual induction will cause a signal to appear at the toroid output which may cause undesired operation.
This is a particular problem with busbars, and more generally with high currents.
To overcome this, a ring with twice the diameter necessary must be used, the live conductors must be properly centred and a sleeve of magnetic material (soft iron-magnetic sheet) may have to be used) (see fig. 10).
When all these precautions are taken, the ratio

$$\frac{I\,\text{phase max.}}{I\Delta n}$$ may be 50,000 or less.

As regards choice of magnetic material
Without entering into the theory of magnetism, one must be aware of a number of constraints: the smaller the earth leakage current to be detected, the greater must be the permeability, and the lower the losses, of the magnetic material. The material must be dimensioned in order to reduce the magnetizing current to a minimum:
■ the transformer must be made to operate at low induction to avoid lack of ampere-turns/induction proportionality and to prevent temperature drift.
Moreover, the signal supplied by the transformer must be capable of causing the associated measuring relay to operate for very large fault currents in relation to its operating threshold. The solution generally consists of compensating the primary ampere-turns by the secondary ampere-turns: causing the transformer to work «on current». This requires a secondary winding of low impedance and a load of low resistance.
Particular attention should be paid to these constraints in the case of separate toroid earth leakage relays, which have a high sensitivity level and are associated with toroids of different diameters widely used in distribution systems.
If the RCD incorporates the toroid the manufacturer can:
■ overcome the problem of centering the live conductors;
■ use materials of lower permeability providing several primary turns (low currents);
■ operate at higher induction to maximize the energy collected and minimize sensitivity to stray inductions (high currents).

Several toroids in conjunction with a single measuring relay
If the (generally electronic) measuring relay only requires a very low value of electrical signal to operate it, the toroids can be made to supply this power.

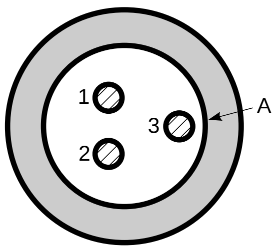
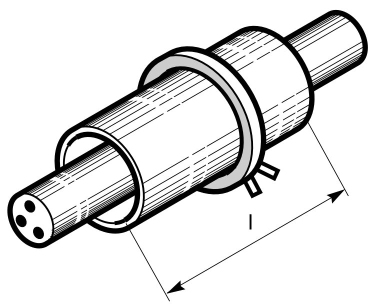


fig. 9: for high currents, place the live conductors in the centre of the toroid.



l = 2 times the ring diameter

fig. 10: for very high currents, insert a magnetic field "regulation" sleeve between the live conductors and toroid.

In this case, «current generator» type toroids can be used. When connected in parallel, they supply an image of the vectorial sum of the primary currents. This circuit is used in earthing systems authorized by the installation standards. However the RCD manufacturer should be consulted.

■ **large incoming cables and aerial feeders** (see fig. 11)
If no commercially available toroid can be installed on the incomer, it is sufficient to place one on each feeder and to connect them in parallel.

■ **cables in parallel** (see fig. 12)
If n cables cannot be passed through the same ring, a toroid can be placed on each cable (comprising all the live conductors) and then be connected in parallel.
But remember:
□ that each toroid sees n (here 3) turns on short-circuit, which may decrease the sensitivity,
□ that if the links have impedance differences, each toroid sees a false zero phase sequence current. This problem can be solved, if these currents are not too large, by connecting the toroids in parallel,
□ this arrangement means that the output terminals S_1-S_2 of each transformer must be labelled to show direction of energy flow.
The above two possibilities must be approved by the manufacturer of the residual current device.

Use of current transformers
(see fig. 13)
The three CTs in parallel, which are current generators, cause a current to flow between A and B which is the vectorial sum of the three currents, and hence the residual earth leakage current.
This Nicholson circuit is commonly used on MV and HV when the earth fault current may reach several tens of amperes.
Care must be taken with the accuracy class of CTs. Thus, with CTs of accuracy class 5 % it is wise not to set the RCD below 10 % of the CT rated current (NF C 13-200 ed. Dec. 89 recommends 10 %) (see fig. 14).

This circuit, which is useful on LV when high currents are involved, generally does not allow settings compatible with the protection of personnel, even with paired CTs:

$$I\Delta n < \frac{U_L}{Ru}.$$

Preferably a toroid should be placed on the line side of the installation, on the earth connection of the transformer LV neutral (see fig. 15).
According to Kirchoff's nodal law, the earth leakage current seen by (1) is strictly the same as that seen by (2).

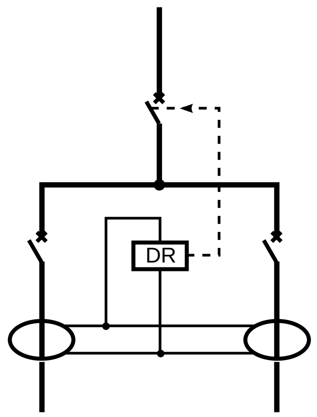


fig. 11: the toroids placed on the feeders and connected in parallel compensate for the impossibility to place a toroid on the incomer.

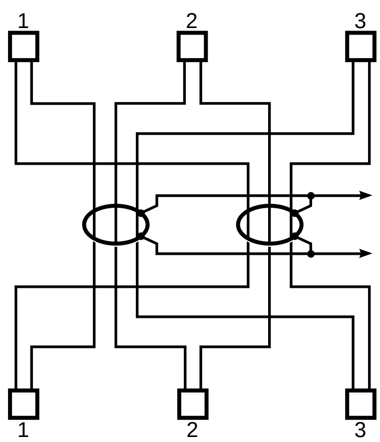


fig. 12: toroid arrangement on large cross section single-wire parallel-connected cables.

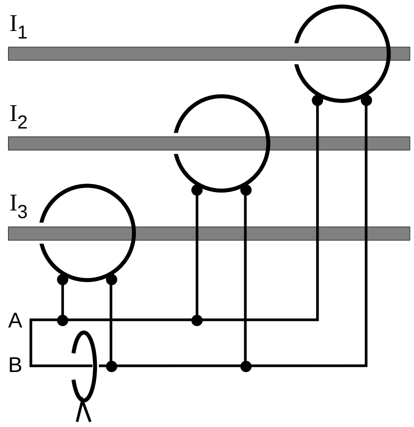


fig. 13: the vectorial sum of the phase currents gives the zero phase sequence current.

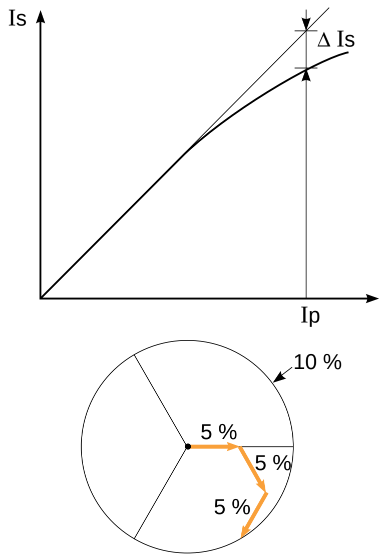


fig. 14: utilization limit of the NICHOLSON diagram.

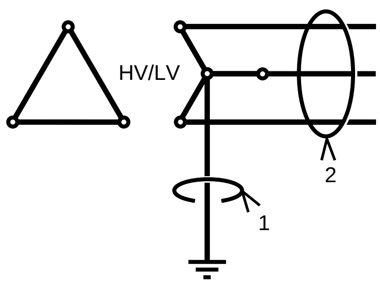


fig. 15: the toroid placed in (1) or (2) gives the same information.

measuring relays

Electromagnetic relays (see fig. 16)
The modern electromagnetic relays used in RCDs employ the principle of magnetic attraction. A very low level electrical energy (100 µVA in some cases) is sufficient to overcome the magnet attraction force and cause the contacts to open by mechanical means.
These relays are particularly suitable for single sensitivity RCDs without time-delay. They are thus found for instance in consumers' main circuit-breakers ($I\Delta n$ = 500 mA).
The toroid and relay combination allows:
■ the live conductors to be given several primary turns;
■ the toroids to work according to the power level (equal impedance of generators and receiver);
■ toroid/relay coupling, if any,on assembly RCDs arranged in this way have a modest cost and are particularly useful in final distribution systems.

Electronic relays
Electronic relays are used in the industrial field, since with electronics adjustable sensitivity and time-delay are easily provided (see fig. 17).
They have the following advantages:
■ a very low pick-up level, of a few **m**VA on the input side (allowing the toroïds to work "on current");
■ precise thresholds and time-delays (and therefore optimum trip discrimination).
These two characteristics make then particularly useful for:
■ separate toroid residual current devices associated with heavy duty circuit-breakers and contactors;
■ residual current devices associated with industrial earth leakage circuit-breakers up to 500 A.
The power required to drive the electronics can be:
■ taken from the fault current itself (as in the case of electromechanical relays) this is the so-called "own current" type of supply;
■ or supplied by the electrical system monitored: this is the "own voltage" type of supply;
■ or supplied by another electrical system: this is the "auxiliary source" type of supply.
The "own voltage" supply is often considered as an "auxiliary source» supply.

Mixed relays
Earth leakage electromechanical relays of the "own current" type require over 100 **m**VA for their operation.
Below this level, the withstand of these relays to mechanical shocks and vibrations is no longer sufficient for industrial purposes.
Since the power is supplied by the fault current, this is a problem with very high sensitivity RCDs (10 mA for example).
The solution consists in placing an electronic accumulator between the toroid and the attracted armature relay; this also allows a precise and reproducible operating threshold to be obtained.
There are other «own current» mixed relays which have been built for different reasons.
At MV, distribution station specification C13-100 required a bank of batteries which caused many problems.
The use of an "own current" electronic relay together with an attracted armature electromechanical trip unit solved the problem satisfactorily as regards both cost and reliability.

Failsafe devices and testing
With reference to RCDs, Standard NF C15-100 para. 532.2.2 states:
«Devices with auxiliary power sources which are not of the failsafe type shall not be used in installations for dwelling premises or for similar applications.
They can be used in installations operated by qualified and experienced personnel.»
A device is of the "failsafe» type if any incident preventing it from working correctly, such as an internal fault or interruption of its auxiliary supply, will automatically cause it to move to its protection position.
Total positive safety, particularly from the internal fault viewpoint does not exist. Thus French RCDs using an auxiliary source are restricted to industrial installations, and "own current" RCDs to domestic and similar installations; this fits in well with their intrinsic capabilities as described above.
In any case, it is advisable to test periodically for internal faults.

fig. 16: the power supplied by the toroid excites an electromagnet whose moving part is held open by a magnet (A). When Id reaches the operating threshold of the differential device, the moving part releases from (A), closes the magnetic circuit and causes the circuit-breaker to open.

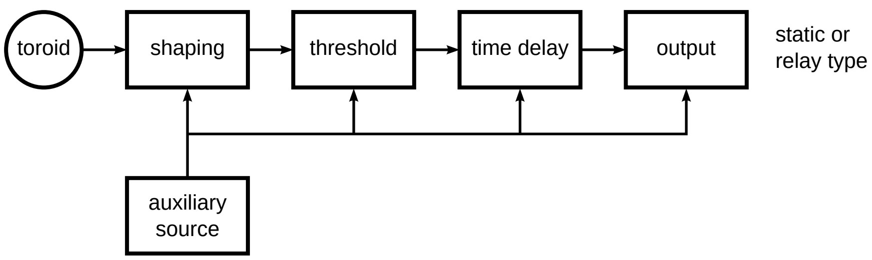


fig. 17: functional diagram of an electronic RCD.

The way in which the test is carried out is important, It must take account of the fact that in any electrical installation there are always capacitive leakage currents to earth, and often resistive leakage currents owing to damaged insulation .
The vectorial sum of all these leakage currents (Id) is seen by the toroid detector and can interfere with the test, particularly if the test circuit is as shown in fig. 18. This test method is very widely used to test the toroid-relay-switchgear combination.
The construction standards limit the test current (1), which may account for the fact that RCDs sometimes do not operate during the test. This is llustrated by the vectorial addition of the leakage current (Id) and the test current (Itest) (see fig. 18).
The test method mentioned above is used for earth leakage sockets and earth leakage circuit-breakers and switches.
As far as separate toroid earth leakage relays are concerned, the same method is sometimes used, but the installer must arrange the test circuit. Because of this, standard UTE 60-130 does not require separate toroid residual current devices to have a test device.
There is another way of testing this type of relay: to test the operation of the relay and the continuity of the toroid relay circuit, including the toroid winding. This principle is used in the Vigirex RH53.

Checking of the operating threshold of a RCD should, even more than the test, be carried out bearing in mind the presence or otherwise of "natural" leakage currents on the downstream circuit.
A good measurement can always be achieved with the downstream circuit disconnected.

Overvoltage effects

Some systems, especially overhead supplied ones, are subject to atmospheric disorders such as lightning. According to how far away the cause is, the LV system may experience any of the following:

■ overvoltage, occurring between the live conductors and the earth (the interference flows off to earth way upstream from the RCDs (see fig. 19a);
■ overcurrent, a part of which flows off to the system downstream from the RCD, in particular by stray capaci-tances (see fig. 19b);
■ overcurrent seen by tthe RCD and due to breakdown downstream from the RCD (see fig. 19c).

Technically speaking, the solutions are well known, e.g.:

■ for electromagnetic relays: placing of a diode in parallel on the relay excitation circuit. This solution is used in consumers' main circuit breakers;
■ for electronic relays: use of a low-pass filter at signal shaping level (see fig. 17).

For more details on stray withstand capacity, refer to the appendix.

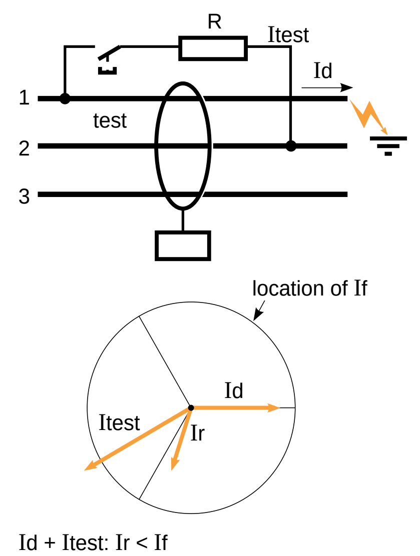


fig. 18: some test circuits made on installation may possibly not operate in the presence of small fault currents.

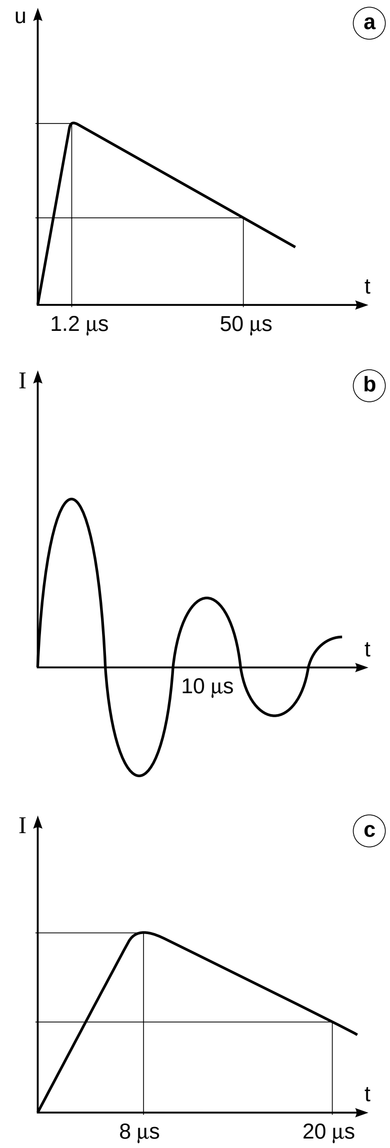


fig. 19: voltage wave and current resulting from lightning.

(1) standard 61-420 states that the test current must not exceed 2.5 IΔn, so that for an RCD that can be used on 220 V or 380 V, i.e.:

$$2.5 \frac{230\ V\ (-20\ \%)}{400\ V} = 1.15\Delta n$$

if supplied at 220 V, - 20 %.

5. different types of RCD technology

RCDs all have the same task: to disconnect the part of the system where an insulation fault has occurred. Depending on their position in different distribution systems, the RCDs differ technically as a function of:

- the associated switching device;
- the risk (direct contact, indirect contact, protection of receivers, etc.);
- the timing requirements (current discrimination or transients, table 2).

production standards

General regulations for the RCDs: IEC 755.
Earth leakage socket: standard in preparation.
Earth leakage load switch: IEC 1008 (NF C 61-140 & 61-141).
Earth leakage circuit-breaker: IEC 1009 (NF C 61-420, 62-411 for LV consumer connection circuit-breakers).
Earth leakage relay : NF C 60-130.
These standards define:

- characteristics of the earth leakage function;
- limits and/or drifts, depending on the environment;
- resistance to mechanical shocks and jolts;
- ambient temperature and humidity;
- mechanical and electrical endurance;
- insulation voltage, surge withstand voltage;
- RCD behavior in the presence of a d.c. component in the fault current (see chapter 7);
- etc.

These standards specify type tests and periodic quality audit and performance tests to be carried out by either the manufacturer or LCIE (NF-USE mark). They provide the user with a product quality and personnel safety guarantee.

Standard IEC sensitivity (IΔn)

- high sensitivity: 6-10-30 mA;
- medium sensitivity: 100-300-500 mA;
- low sensitivity: 1-3-10-30 A.

Trip curves
These take account of world-wide studies on electrical risks (IEC 479), in particular:

- effects of current (direct contact protection);
- safety voltage and safety curve (indirect contact protection).

Direct contact (IΔn < 30 mA)
At the present time, CENELEC countries still place their relays in classes T01 or T02.
The IEC is planning to standardize an operating curve located in zone 2 of figure 6 which is less restrictive than curve T02 (see fig. 20).

Indirect contact $\left(t_f = f\left(\frac{Id}{I\Delta n}\right)\right)$

Until 1994, the reference in certain standards (e.g. NF C 61-140) was CENELEC curves T1 and T2.
In 1993, IEC 755 has introduced two curves TA and TB, (see fig. 21).
NF C 62-411 (LV consumer connection) and IEC 1008 and 1009 (earth leakage switches) currently define two tripping curves: (see fig. 22):

- curve (G) for instantaneous RCDs;
- curve (S) for selective RCDs of the lowest time delay level.

Both these curves correspond to the table in fig. 23.
With the devices complying with these curves, the user now has a complete range of «domestic and similar» RCDs allowing:

- firstly, the elaboration, as required, of the various discrimination diagrams described in paragraph 536.3.3 of standard NF C 15-100;
- secondly, the use of surge arresters.

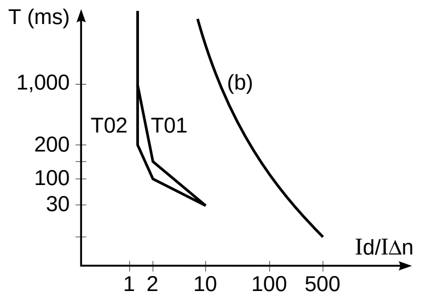


fig. 20: class 5 "tripping" of "direct contact" RCDs as in CENELEC, and curve B of IEC 479-1 (fig. 6).

earth leakage socket and earth leakage extension

There are several technical solutions (described in the previous paragraph):

- electromagnetic attracted armature relay for 30 mA;
- mixed relay (with electronics) for 10 mA.

earth leakage load switch and earth leakage circuit-breaker < 100 A

The technology used is generally that of the magnetic attraction relay (see fig. 24), for the 30 mA -300 mA and 500 mA sensitivity levels of non-time-delayed RCDs (see fig. 25).
The S type RCDs have, in addition to the magnetic relay, an electronic time delay (see fig. 26).

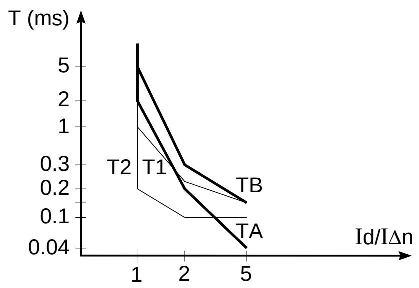


fig. 21: RCD tripping curves as in:
- *IEC 755 (TA and TB);*
- *NF C 61-140 (T1 and T2).*

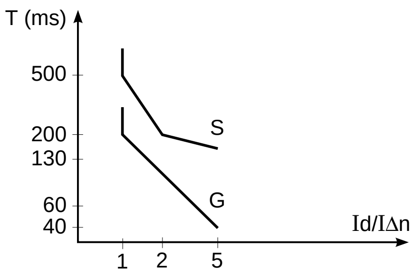


fig. 22: maximum operation time curves for the selective connection circuit-breaker (S) and for the instantaneous "general" circuit-breaker (G).

industrial earth leakage circuit-breaker 100 to 630 A

In the devices mentioned above the live conductors can have several primary turns (3 to 5) around the toroid; but for currents of over 100 A the primary has only one turn and the toroids are screened to minimise the asymmetry effects described previously (see fig. 12 and 13). This means that the 30 mA sensitivity level is almost unobtainable with an electromagnetic relay alone. Since these circuit breakers are mainly used in industrial distribution, and discrimination is thus required, the most suitable technology is the electronic relay. The latter comes in the form of a separate unit, often referred to as a «Vigi module» (see fig. 27).
The reference standard is IEC 947-2 appendix B.

earth leakage relays

(separate toroid type)

These are required in industry to provide earth leakage protection if the associated switchgear is a contactor or a non-earth leakage circuit-breaker

Since rated current varies for the most part, these relays are often associated with toroids of various diameters (see fig. 28) and must allow for provision of high, medium or low sensitivity protection with time delay. They are thus mainly the electronic type (see fig. 27 and 29).
The earth leakage relays used at MV are similar to the LV electronic relays (with higher thresholds and longer time delays).

type	In(A)	IΔn(A)	normalized value of operating and non-operating time (s) at:				
			IΔn	2 IΔn	5 IΔn	500 A	
general (instantaneous)	any value	any value	0.3	0.15	0.04	0.04	maximum operating time
S	≥ 25	> 0.030	0.5	0.2	0.15	0.15	maximum operating time
			0.13	0.06	0.05	0.04	minimum non-operating time

fig. 23: normalized values of maximum operating time and of non-operating time.

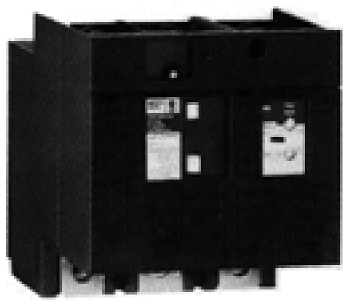


fig. 27: VIGICOMPACT earth leakage module.

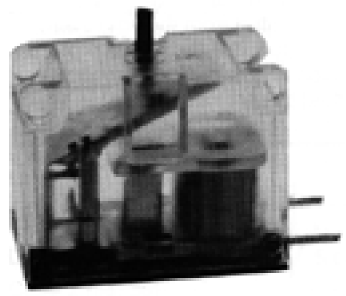


fig. 24: attracted armature relay.

fig. 28: toroids for electronic earth leakage relays.

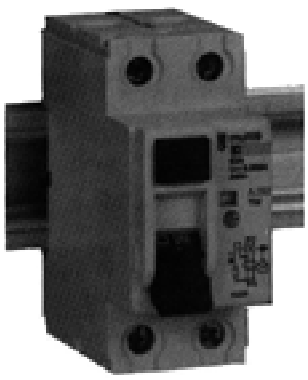


fig. 25: earth leakage switch.

fig. 26: connection circuit-breaker.

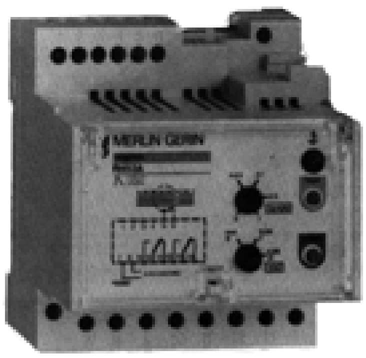


fig. 29: electronic earth leakage relay.

6. coordination of protection

The aim of coordinating protection is, in addition to ensuring protection of people, to limit, select and disconnect only the faulty part of the installation.
The principle for earth leakage protection and for short-circuit protection (current and time discrimination) is the same.

“vertical” discrimination

The earth leakage fault current is not limited, as in the case of a fault current, by system impedance, but by:
■ either the resistance of the return circuit (neutral and consumer earths);
■ or by the impedance of the fault loop if all the frames are interconnected by a main equipotential bond.
The earth leakage fault current is not limited as is a short-circuit current, by system impedance, but by the resistance of the return circuit (neutral and consumer earths), or, if all the frames are interconnected by a main equipotential bond, by the impedance of the fault loop.
This means that the closer the fault is to the terminals the greater will be the earth leakage current. Discrimination must thus be current and time-sensitive (see fig. 30).
Using current discrimination, the non-trip condition of (1) for a fault downstream from (2) is $I\Delta n(1) > 2\, I\Delta n(2)$

for: $\frac{I\Delta n}{2} \leq If \leq I\Delta n$

and using time discrimination

$t_{r(1)} > t_{r(2)} + t_{c(2)}$

where t_r = trip time delay = non-operating time
t_c = time between the breaking signal given by the measuring relay and the moment of breaking (arcing time included).
Since time-delay relays are electronic, account must be taken of the «drop-off» (threshold circuit fault memory): t_m (see fig. 31) to ensure that at every discrimination stage the following is obtained:

$t_{r(n)} > t_{r(n-1)} + t_{c(n-1)} + t_{m(n)}$

or

$t_{r(n)} > t_{f(n-1)} + t_{m(n)}$.

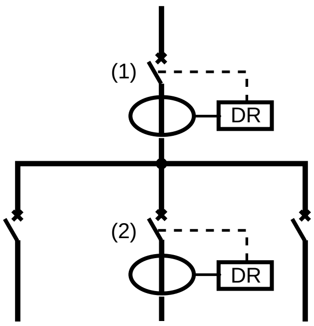


fig. 30: vertical time discrimination.

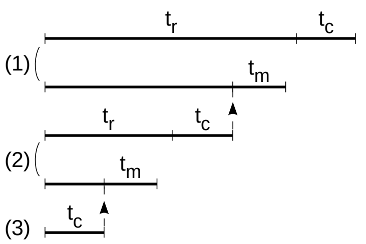


fig. 31: the time delay difference must allow for the breaking time of the downstream breaking device and for the memory time of the upstream relay.

Practical example
Vigi MH or MB modules at $2I\Delta n$ where:
t_f = total operating time = $t_r + t_c$,
■ setting 0 t_r = 0 ms t_f < 40 ms;
■ setting I t_r = 60 ms t_f < 140 ms;
■ setting II t_r = 150 ms t_f < 300 ms;
■ setting III t_r = 310 ms t_f < 800 ms.
The relays are of the constant time type, which means:
t_f = constant for $Id > 2I\Delta n$.
Difficulties may be encountered with this discrimination if it becomes necessary to alternate earth leakage circuit-breakers with earth leakage relays, because:
■ the earth leakage circuit-breaker is specified by time-delay t_r;
■ the earth leakage relay is specified by its own operating time or time-delay, t, corresponding to the time elapsing between the appearance of the fault and the transmission of the opening signal to the circuit-breaker or contactor (see fig. 32 and 33).
In all cases, start from the final distribution, return towards the line side of the installation and calculate the successive t_f and t_r (or t) values (at $2I\Delta n$).

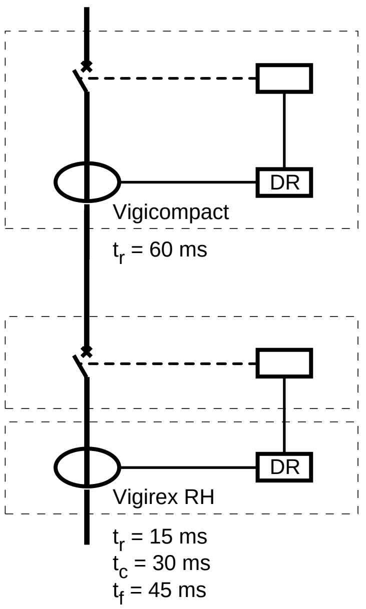


fig. 32: time discrimination example.

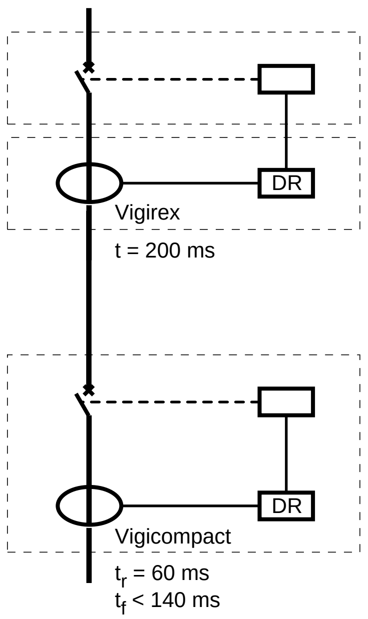


fig. 33: time discrimination example.

"lateral" discrimination

This is covered by French standard NF C 15-100, para. 536.3.2. It saves the use of an earth leakage circuit-breaker at the supply end of the installation if the various circuit-breakers are in the same panel.
If there is a fault, only the faulty feeder is disconnected, since the other earth leakage devices do not see the fault current (see. fig. 34).
The 2 (or n) earth leakage devices can have an identical t_r (or t). In practice, some devices sometimes trip «in sympathy».

Here are two examples:

Case 1 (fig. 35)
(1) a consumer who is a powerful generator of overvoltages (e.g. a welding machine),
(2) a long no-load system or system with filter (computer feeder).
Opening of D_1 causes an overvoltage which leads to a capacitive current to earth (stray capacitances to earth are unbalanced) on the feeder protected by D_2.
Consequently, the residual device of D_1 can be instantaneous, and that of D_2 must be time-delayed.
The residual device (D_2) must in any case be time-delayed, because when D_2 closes, the capacitances (stray or otherwise) will cause a damped oscillatory earth leakage current.
Example: IBM5410 with suppression filter:
the measurement shows:
Id: 40 A (first peak), f = 11.5 kHz.
Damping time constant (66 %):5 cycles.

Case 2 (fig. 36)
If the insulation fault on phase 1 of feeder 2 is a dead short-circuit it brings this phase to earth potential (the further from the source in the TT earthing system or in fire protection in unearthed neutral system, the more applicable this is).
The capacitive current supplied by feeder 1 will cause the corresponding residual device to operate «in sympathy».
These two examples show that it is necessary to time-delay the residual devices on long feeders or feeders having filters, so that the response time setting of the residual devices in the final distribution stage may be different.

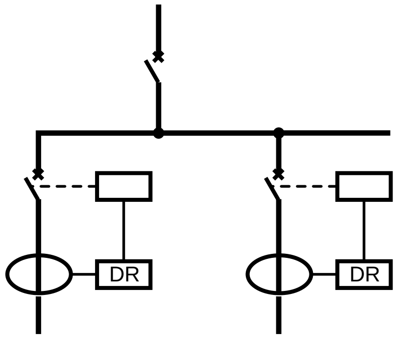


fig. 34: lateral discrimination example or "circuit discrimination".

HV discrimination

At HV, each circuit-breaker is associated with a relay which often provides simultaneous short-circuit and earth fault protection (called «zero phase sequence» because of the symmetrical component theory: (see "Cahier Technique" n° 18).
HV circuit-breakers have an electro-dynamic withstand sufficient for time discrimination to be used for short-circuits, and naturally also for earth faults; this explains coupling of the two protections, which then use the same time-delay unit.
As for LV time-sensitive discrimination, account must be taken of the drop-off time of the relays.
At HV, instantaneous zero phase sequence relays are not used since it is easy for accidental tripping to occur, for example for the following reasons:
- external overvoltages (atmospheric);
- internal overvoltages: closing of a line on no-load, on-load breaking;
- capacitive exchanges during faults;
- non-linear response of the Nicholson circuit (common to the three CTs) because of the dispersion of CT characteristics and in particular because of the d.c. component occurring during a short-circuit or during asymmetrical closing;
- presence of third harmonics (see "Cahier Technique" n° 113).

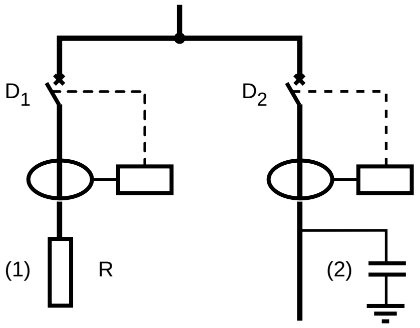


fig. 35: some feeders must be fitted with time-delayed RCDs.

"Vertical" discrimination

is used, as for LV, with operating threshold settings according to the type of neutral earthing
(see "Cahier Technique" n° 62).
- direct, via resistance, or zero phase sequence generator (EDF example: 300 A overhead and 1000 A under-ground);
- with time-delay settings generally in 0.3 sec. steps, unless logic discrimination is used (see "Cahier Technique" n° 2).

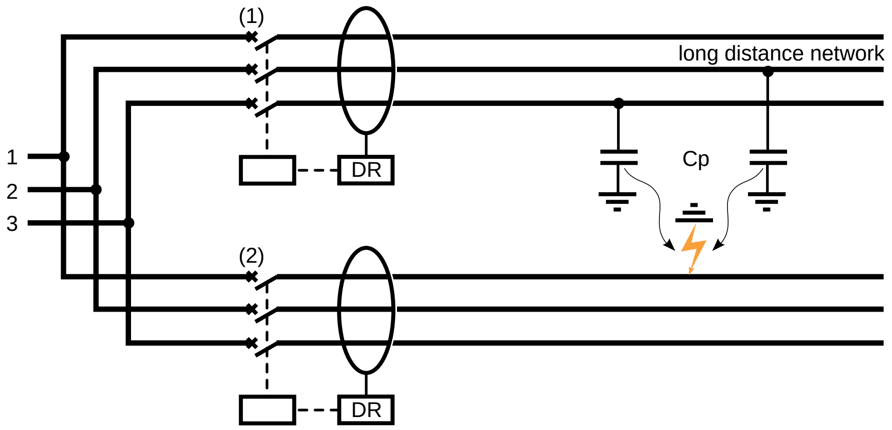


fig. 36: untimely tripping by "sympathy" if the RCDs are not time-delayed.

“Lateral” discrimination

■ is used as in LV in direct and impedance earthed neutral systems;

■ with unearthed neutral (industrial installations < 10 kV in general): this earthing system is chosen to restrict the fault current to a minimum and to allow continuity of service. The stray capacitances can take the place of a zero phase sequence generator.

Two cases may arise:

□ use of the natural capacitive impedance of the system and conventional earth leakage relays: the whole system has a minimum stray capacitance

$$C = \frac{\sum C}{2} \text{ for example}$$

each feeder has a stray capacitance C_1, C_2, C_3, etc..., each less than C/1.5 (see. fig. 37).

It is then sufficient to set the zero phase sequence relay of feeder (i) to a threshold Ih such that:

$$I_{ci} < I_h < \frac{I_c}{1.5},$$

□ use of the natural capacitive impedance of the system and zero phase sequence directional relays. These relays only operate if the reactive power is flowing downstream, and thus provide lateral discrimination at an operating threshold which may be lower than for conventional relays, e.g. 1 A for each feeder in the diagram in figure 37.

This is costly but necessary for certain system configurations.

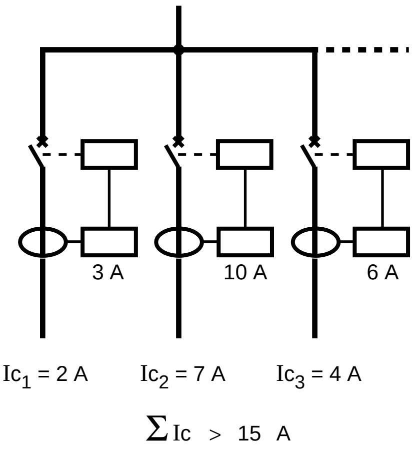


fig. 37: lateral discrimination example without zero phase sequence generator.

7. special cases of direct current and mixed systems

fewer risks for people

Experiments (see fig. 5) show that people are roughly five times less sensitive to direct current than to alternating current at 50/60 Hz for low currents.

Ventricular fibrillation is only a risk above 300 mA.

Installation standards IEC 364 and IEC 479 stipulate a ratio limited to 2, given that in practice fault currents are directional but not always smoothed. This is illustrated in the table in figure 7 which gives tripping times as a function of contact voltage (which generates dangerous current). This table is given as a «safety» curve in figure 38, which clearly shows that a voltage of 120 V d.c. corresponds to a voltage of 50 V a.c. (with ripple factor ≤ 10 %).

Moreover, reference to the widely found circuit illustrated by circuit G in figure 42 shows that the fault voltage of 200 V d.c. generated by this bridge type corresponds to an alternating voltage of roughly 100 V and to a maximum breaking time of 0.4 s.

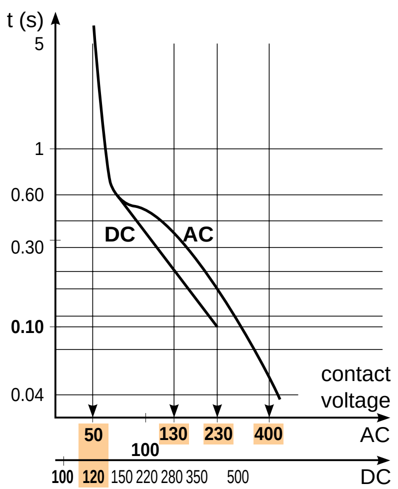


fig. 38: curves drawn up from the maximum breaking times of a RCD defined by IEC 479-1 (as in the table in figure 7) contact voltage.

RCD standards

The standards are reviewed below:

■ IEC 755: «general rules for RCDs» and French standards;

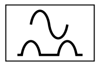
■ NF C 61-140 and 61-141: «earth leakage switches»;

■ NF C 61-420: «small earth leakage circuit-breakers»;

as well as

■ IEC 947-2 appendix B: «industrial earth leakage circuit-breakers».

These standards allow for the existence of non-alternating currents and define the standard cases presented in figure 39. They describe the corresponding tests. For example earth leakage switches must operate for $I_D \leq 1.4\ I\Delta n$ in all cases corresponding to figure 40 with or without a superimposed smoothed direct current of 6 mA. The fault current is applied either suddenly or by slowly building up from 0 to 1.4 IΔn in 30 s.
Products which have satisfactorily passed these tests have the symbol

on their front panel 

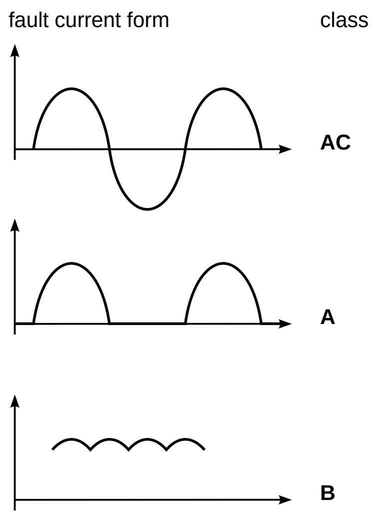


fig. 39: fault currents specified by RCD construction standards fault current form class.

real fault currents

These reflect the voltages present between the fault point and the installation neutral. The wave form of the fault current is very rarely the same as that of the voltage or current applied, delivered with the load.
Fault currents and voltages of the pure d.c. type (zero ripple) are extremely rare, which explains why type B RCDs are only exceptionally marketed by manufacturers.

In domestic supply situations
Distribution and rectifier circuits are single-phase. These circuits correspond to diagrams A to F in figure 41. Type A RCDs ensure protection of people and only detect fault currents supplied by diagram B if they suddenly occur. In industry, most rectifier circuits are three-phase (diagrams G to K in figure 42).

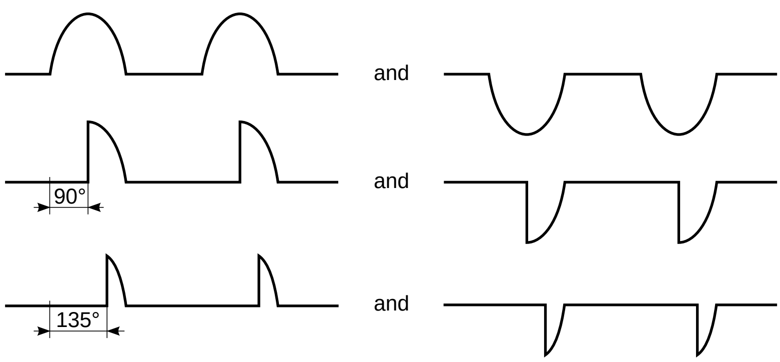


fig. 40: wave form of class A RCD test currents

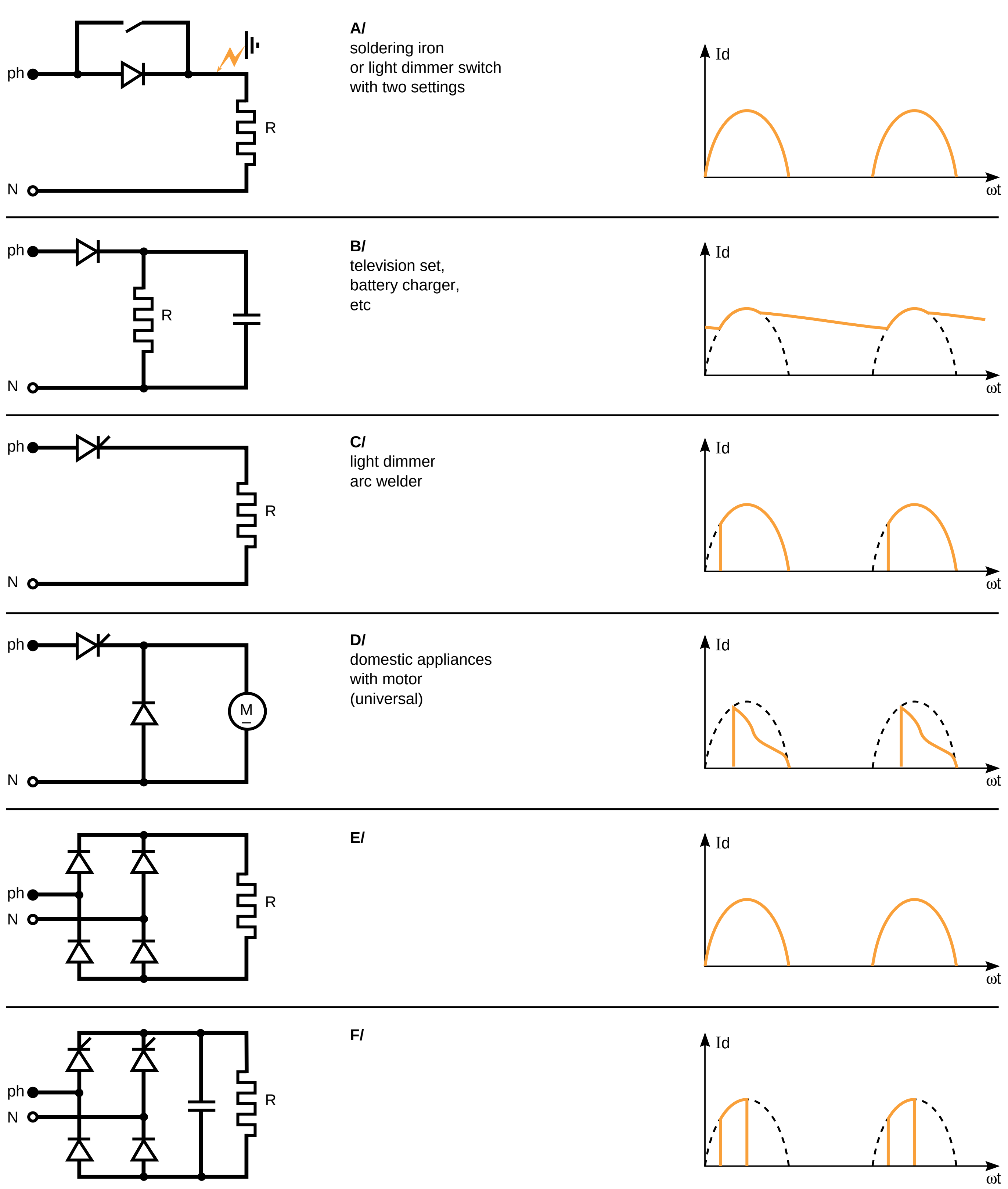
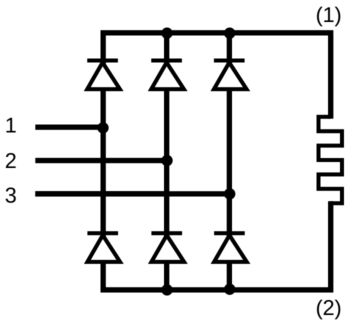
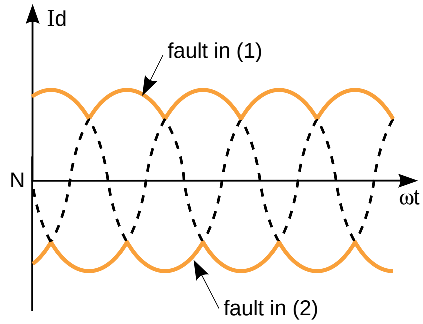
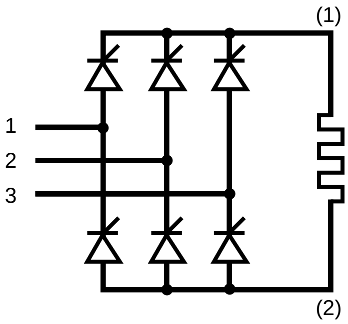


fig. 41: single phase circuit rectifiers and wave form of fault current.



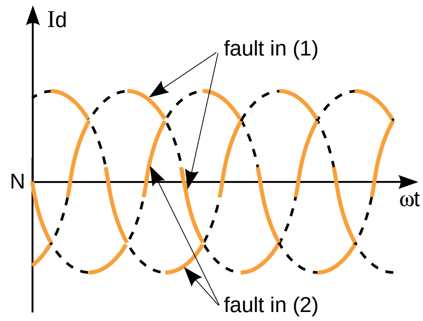
G/
welding rectifier,
electromagnet,
electrolysis,
etc

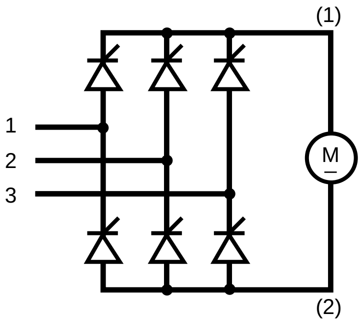




H/
controlled rectifier
for:
- industrial d.c. system;
- electrophoresis

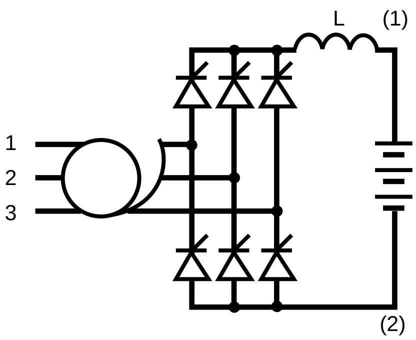
The fault current at (1) follows the peaks of the conduction zones. The same applies to the fault at (2) but following the valleys



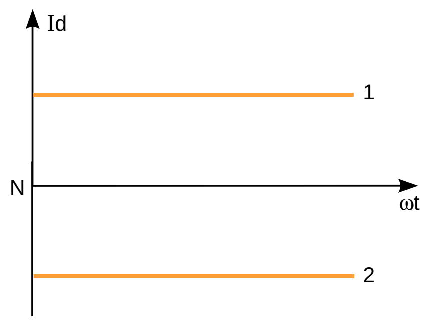


J/
speed controller
for d.c. motor

The fault current is "pulsed" at low speeds and is very close to the pure d.c. current at high speeds



K/
stationary battery charger for:
- d.c. auxiliary system;
- inverter



Note
In this example, the smoothing inductance (L) causes the thyristors to conduct (cyclically and in pairs) so that the fault point (1) or (2) is always electrically connected to neutral;
the fault current therefore almost pure d.c.

fig. 42: three phase circuit rectifiers and wave form of fault current.

Some circuits may generate a d.c. fault current with low ripple factor:

■ circuits G and H

Circuit G supplies a rectified voltage with a continuously low ripple factor, making it hard for RCDs to detect fault currents. On the other hand, circuit H generates very chopped fault currents, easily seen by the RCDs. However during full wave conduction this type of circuit becomes equivalent to circuit G.

■ circuit J

This is the most common circuit, in particular for speed controllers. Because of the counter-emf of the motor and its inductance, it generates more smoothed fault currents than circuits G and H above.

The RCDs placed upstream from the speed controller must be able to provide protection, whatever the thyristor conduction angle.

Some standard RCDs may be suitable provided threshold I∆n is adjusted accordingly.

For example, figure 43 gives the sensitivity of a RCD of similar electronic technology, as a function of the output voltage.

■ circuit K

This circuit does not produce the d**j**/dt vital for operation of the RCD magnetic detectors and is thus dangerous unless a transformer is used instead of an auto-transformer, since the existing RCDs cannot provide the necessary protection.

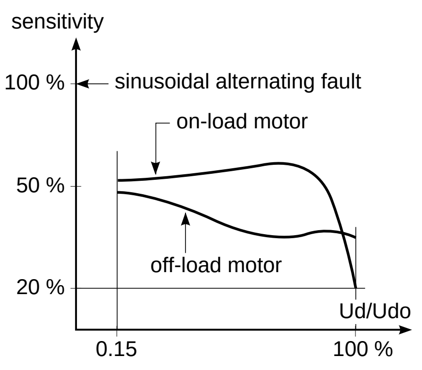


fig. 43: evolution of the sensitivity of an electronic RCD placed upstream from a thryristor rectifier.

"Cahier Technique" n° 129 deals with protection of people and with inverters in more detail.

direct current return

Going back to industrial circuit G, let us see what happens if a second fault occurs on the a.c. part of the system (see fig. 44).

If the RCD (1) has been badly chosen or is inoperative for any reason, it will fail to clear the insulation fault occurring on the d.c. part.

If a fault occurs on an a.c. feeder, the current seen by the corresponding RCD (see fig. 44) will be $i_1 + i_2$.

Para. 532-2.1.4 of standard NF C 15-100 specifies: «if electrical devices capable of producing direct currents are installed downstream from a residual current device, precautions shall be taken to ensure that in the event of an earth fault the direct currents

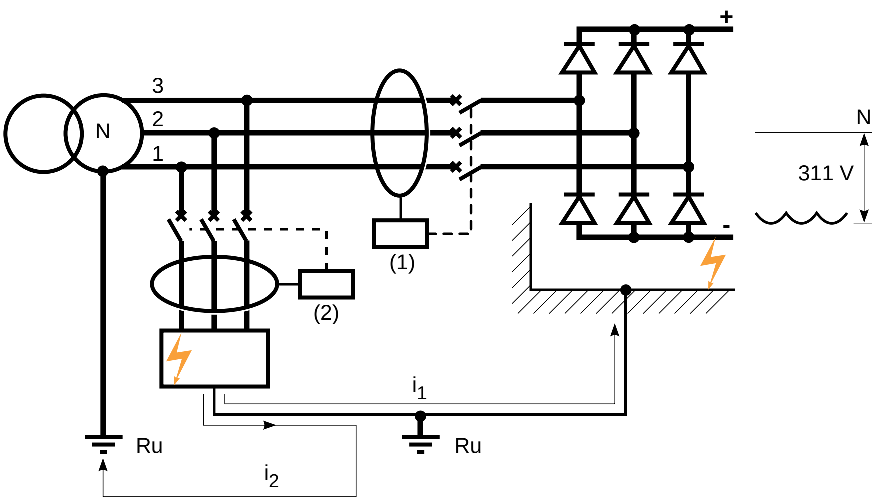


fig. 44: the RCD (2) may be blinded by the current of a fault occurring behind the rectifier if it is not cleared by the RCD (1).

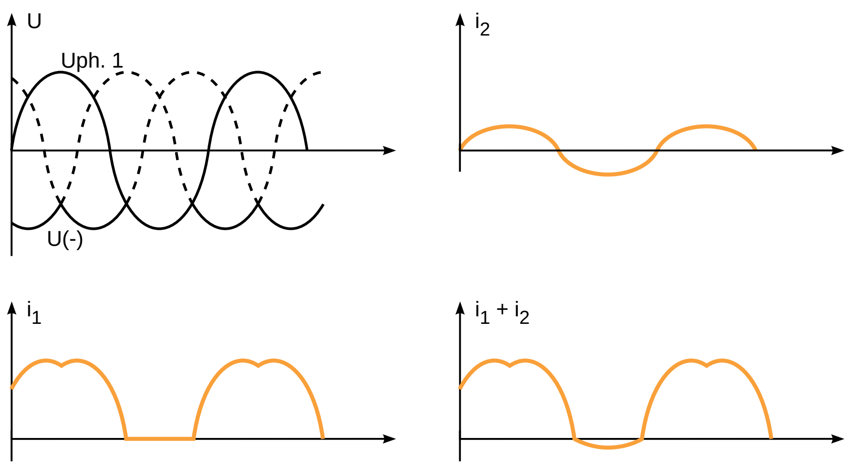


fig. 45: form of the fault current that may be "seen" by the RCD (2) in figure 44.

will not interfere with operation of the RCDs and will not jeopardise safety».
It is thus advisable to:
■ carefully choose the RCD placed just upstream from a rectifier system;
■ if necessary use class A RCDs in the rest of the installation.

technological solutions

All RCDs use magnetic toroid detectors. It is an established fact that if the toroid is saturated by a d.c. component (see fig. 46), as in Lenz's law $e = \frac{d\varphi}{dt}$ voltage cannot be developed.
Type A RCD toroids will therefore have a high saturation current.
Moreover, for the toroid to give an output signal, magnetic material must be used which does not present a horizontal saturation curve.

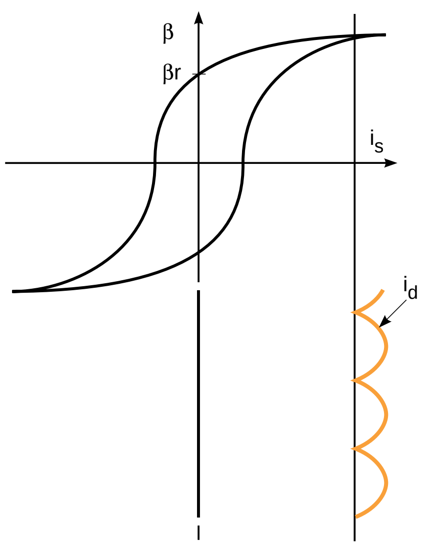


fig. 46: if the tore is satured, it cannot measure a low fault current.

Flat magnetisation curve materials, with a small remanent induction b_r, solve this problem (see fig. 47).
These materials are generally used alongside a capacitor, thus ensuring resonance in the secondary toroid circuit. Use of these techniques makes it possible at present to produce class A RCDs of the electromechanical and electronic type.
Although the market is limited for class B RCDs (only diagram K is concerned), technological solutions do exist. For example a toroid can be used as an oscillator component, the oscillator being destabilized when d.c. current flows through the toroid.

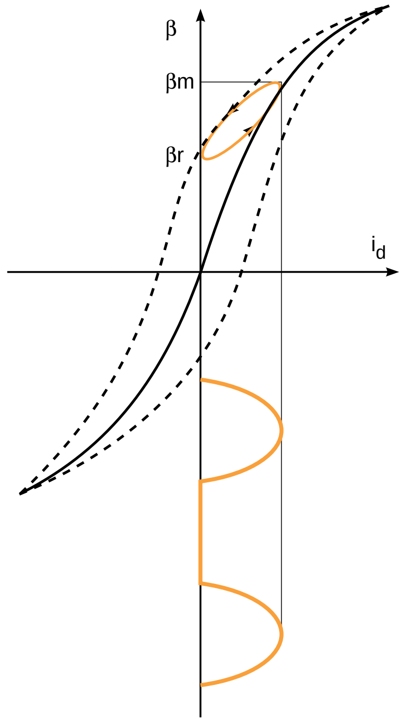


fig. 47: flat magnetic curve materials can measure AC and directional currents.

8. conclusion

At a time when electricity, as a source of power, is playing an increasingly important role in the home, in large institutions and in industry, it is appropriate to recall the risk of electrocution, to quantify it, and to improve our knowledge of Residual Current Devices.
In common with all types of equipment, these devices have their strengths and their weaknesses. These devices are capable of further improvement and are destined to play an increasingly important role in the protection of personnel and equipment. All industrialized countries employ RCDs on a very wide scale with different earthing systems both in industry and in the home. In France, use of RCDs is still growing: high sensitivity 30 mA devices are now compulsory on domestic circuits supplying special risk areas and sockets. By providing a better knowledge of earth leakage devices, this study contributes to the safety of everyone.

RCD and EMC

EMC (Electromagnetic Compatibility) is the mastery of electric interference and of its effects.
Construction and installation precautions must be taken for the RCDs in common with all sensitive and/ or electronic devices.
The main cause of interference is overvoltage (converted into current waves) as a result of lightning and the «operations» of the switchgear on electric systems.

Overvoltages (see fig. 48 and 49) can affect electronic RCDs through their auxiliary power supply. To prevent such harmful effects (component destruction, nuisance tripping), the supply circuits of Merlin Gerin RCDs are fitted with transformers and overvoltage limiting devices (Transil, G Mov), (see fig. 7): «auxiliary source».
For the same reason, auxiliary supply of electronic devices by capacitive dividers is not recommended. Still to avoid overvoltage effects, we advise, when using separate toroid RCDs, the use of a shielded pair, and even of a twisted shielded pair, between relay and toroid: the shielding is connected to the relay frame.

Overcurrents (see fig. 50 and 51)
When of the common mode, as is the case with lightning, they flow through the toroid like a fault current to earth. All Merlin Gerin RCD types are immunized against these stray currents. The corresponding test, stipulated by construction standards, corresponds to the symbol in figure 52.
To be more precise, as an axample, the french standard NF C 61-402 prescribes for all RCDs utilized in final distribution the following tests:
- voltage waveform: 1.2 **m**s;
- oscillating current: 0.5 **m**s - 100 kHz-200 A;
- transient burst, level 4 kV;
- electrostatic discharge, level 8 kV;
- electromagnetic radiation according to NF C 46-022.

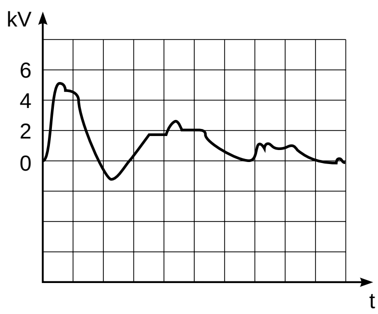


*fig. 48: (t = 20 **m**s par square): overvoltage between phase and earth at the consumer's location as a result of a lightning stroke (EDF source).*

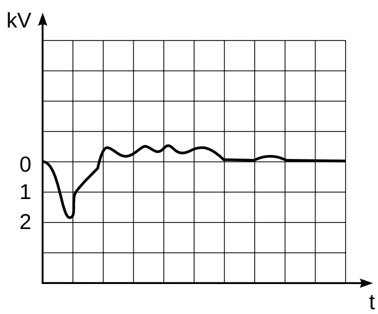


*fig. 49: (t = 20 **m**s per square): overvoltage between phase and earth at the consumer's following to operation of a HV protection (EDF source).*

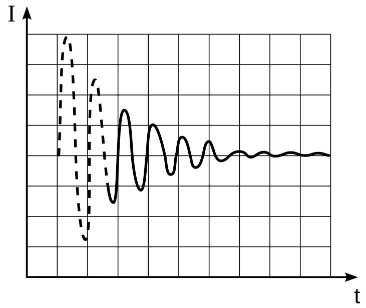


*fig. 50: (t = 5 **m**s per square - I = 10 A per square): transient current wave occuring on closing of a highly capacitive current.*

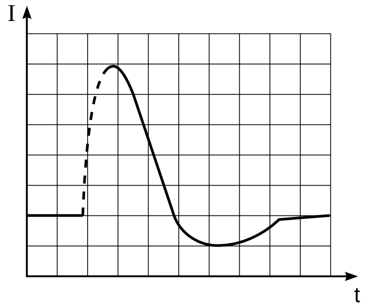


*fig. 51: (t = 5 **m**s per square - I = 40 A per square): lightning current wave.*

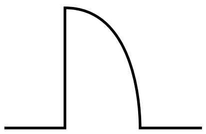


fig. 52: earth leakage devices immunized against stray currents.

10. bibliography

Standards

- IEC 364-3: Electrical installations of buildings - Assessment of general characteristics.
- IEC 479: Effects of current passing through the human body.
- IEC 755: General requirements for residual current operated protective devices.
- IEC 947-2: part 2: Circuit-breakers.
- IEC 1008: Residual current operated circuit-breakers without integral overcurrent protection for household and similar uses (RCCB's).
- IEC 1009: Residual current operated circuit-breaker with integral overcurrent protection for household and similar uses (RCBO's).
- UTE C 60-130: Current-operated earth-leakage protective devices (devices DR) for installations rated up to 1,000 volts: requirements.

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