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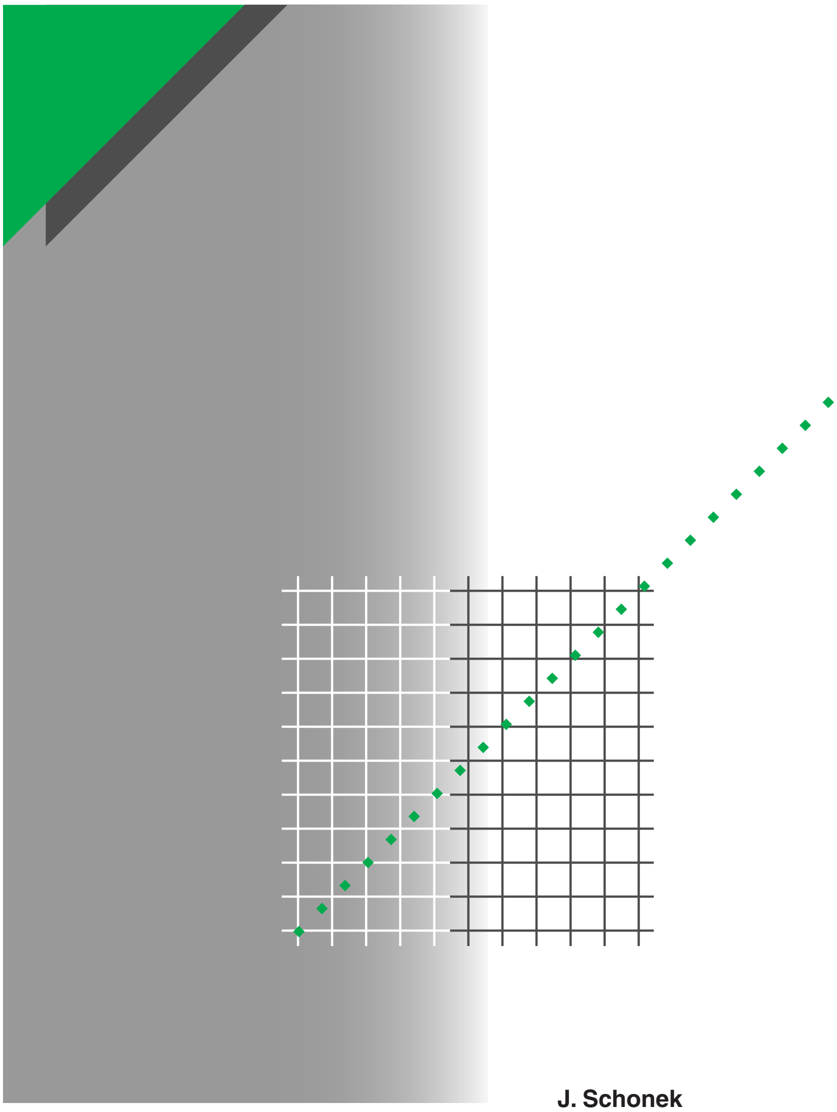
Residual current devices in LV



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Foreword

no. 114

Residual current devices in LV

Jacques Schonek

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He then went on to manage the harmonic-filtering activity.
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Lexicon

Common mode disturbance
Any continuous or transient electromagnetic phenomenon occurring between a live part of a power system and earth. May be a transient overvoltage, a continuous voltage, an overcurrent or an electrostatic discharge.

Differential mode disturbance
Any phenomenon between different live parts of a power system, e.g. an overvoltage.

Direct contact
Contact of a person with the live parts of electrical devices (normally energised parts and conductors).

Earth-leakage current
Current that flows from the live parts to earth, in the absence of an insulation fault.

Electrisation
Application of voltage between two parts of the body of a living being.

Electrocution
Electrisation resulting in death.

Exposed conductive part (ECP)
Conductive part likely to be touched and which, although normally insulated from live parts, may be energised up to a dangerous voltage level due to an insulation fault.

Fault current I_d
Current resulting from an insulation fault.

Indirect contact
Contact of a person with accidentally energised exposed conductive parts (ECP), usually due to an insulation fault.

Insulation
Arrangement preventing transmission of voltage (and current flow) between a normally energised part and an exposed conductive part (ECP) or earth.

Insulation fault
Break in insulation causing an earth-fault current or a short-circuit via the protective conductor.

Intentional leakage current
Current that flows to earth via the intentionally installed components (resistors or capacitors), in the absence of an insulation fault.

Live conductors
Set of conductors for electrical power transmission, including the neutral, with the exception of the PEN conductor for which the “protective conductor” (PE) function takes priority over the “neutral” function.

Natural leakage current
Current that flows to earth via the insulation, in the absence of an insulation fault.

Neutral system
See "System earthing arrangement".

Protective conductors (PE or PEN)
Conductors which, according to specifications, connect the exposed conductive parts (ECP) of electrical equipment and certain other conductive parts to the earth electrode.

Rated residual operating current $I\Delta n$
Value of the residual operating current assigned by the device manufacturer at which the device must operate under the specified conditions.
According to construction standards, at 20 °C, low voltage residual current devices must operate at residual currents between $I\Delta n/2$ and $I\Delta n$

Residual current
Algebraic sum of the instantaneous values of the currents flowing through all live conductors in a circuit at a point of the electrical installation.

Residual current device (RCD)
Device whose decisive quantity is the residual current. It is normally associated with or incorporated in a breaking device.

Residual operating current
Value of the residual current causing a residual current device to operate.

System earthing arrangement (SEA)
Also referred to as the neutral system, earthing system or earthing arrangement.
Standard IEC 60364 stipulates three main types of earthing arrangements that define the possible connections of the source neutral to earth and of the exposed conductive parts (ECP) to earth or the neutral. The electrical protection devices are then defined for each one.

Touch voltage limit (U_L)
Voltage U_L below which there is no risk of electrocution.

Ventricular fibrillation
A malfunctioning of the heart corresponding to loss of synchronism of the activity of its walls (diastole and systole). The flow of AC current through the body may be responsible for this due to the periodic excitation that it generates. The ultimate consequence is stoppage of blood flow.

Residual current devices in LV

Today, residual current devices (RCD) are recognised as the most effective means of protecting life and property against electrical hazards in low-voltage systems.

Their selection and optimum use require sound knowledge of the principles and rules governing electrical installations and in particular system earthing arrangements as well as existing technologies and their performance levels.

All these aspects are dealt with in this "Cahier Technique", with in addition numerous answers provided by Schneider Electric technical and maintenance departments to frequently asked questions.

Contents

1 Introduction

Compared to other energy sources, electricity has many advantages, but also many risks. It is used on a daily basis by the general public and many accidents still occur, resulting in burns, fires and electrocution.

Strict installation rules have been set up by international (IEC, CENELEC) and national (e.g. NFPA in the USA and UTE in France,) organisations.

Dependable protective devices have been designed by carefully analysing the risks and consequences of equipment failures or incorrect use. Among these devices, RCDs (residual current devices) are recognised by international standardisation organisations as an effective means to protect life and property.

This document will present the subject in three steps:

- a description of the risks related to electrical currents,
- an overview of the protection techniques employed to limit those risks,
- an in-depth presentation of how RCDs operate.

2 The risks of electrical currents

2.1 Electrisation of persons

A person subjected to an electrical voltage is electrised. Depending on the level of electrisation, the person may be subjected to different pathophysiological effects:

- disagreeable sensation,
- involuntary muscular contraction,
- burns,
- cardiac arrest (electrocution).

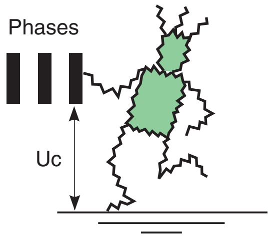
These effects depend on various factors, including the physiological characteristics of the person, the environment (e.g. wet or dry conditions) and the characteristics of the current flowing through the body.

A person may be subjected to an electrical shock in two manners:

- direct contact, e.g. the person touches an energised, bare conductor,
- indirect contact, e.g. the person touches a metal part of an electrical machine or device with an insulation fault.

The dangerous aspect is the current (magnitude and duration) flowing through the human body and particularly near the heart.

a) Direct contact



b) Indirect contact

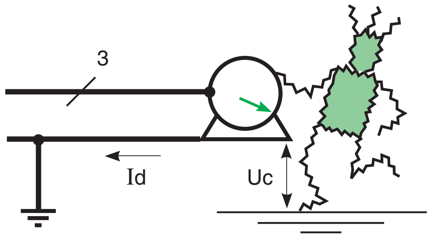


Fig. 1 : Direct and indirect contact.

Figure 2 sums up the work of the International Electrotechnical Commission on the subject (standard IEC 60479-1, Ed.4, 2005, Effects of current on human beings and livestock - Part 1. General aspects). It indicates the consequences of AC current flowing through the human body, from the left hand to the feet, depending on the current and its duration.

It is especially important to consider zones AC-3 and AC-4 where there is real danger.

- Zone AC-3 (between curves B and C_1)

Usually no organic damage, but there is a likelihood of muscular contractions and difficulty in breathing, with reversible disturbances in the formation and conduction of impulses in the heart.

- Zone AC-4 (located to the right of curve C_1)

In addition to the effects noted for zone AC-3, the probability of ventricular fibrillation:

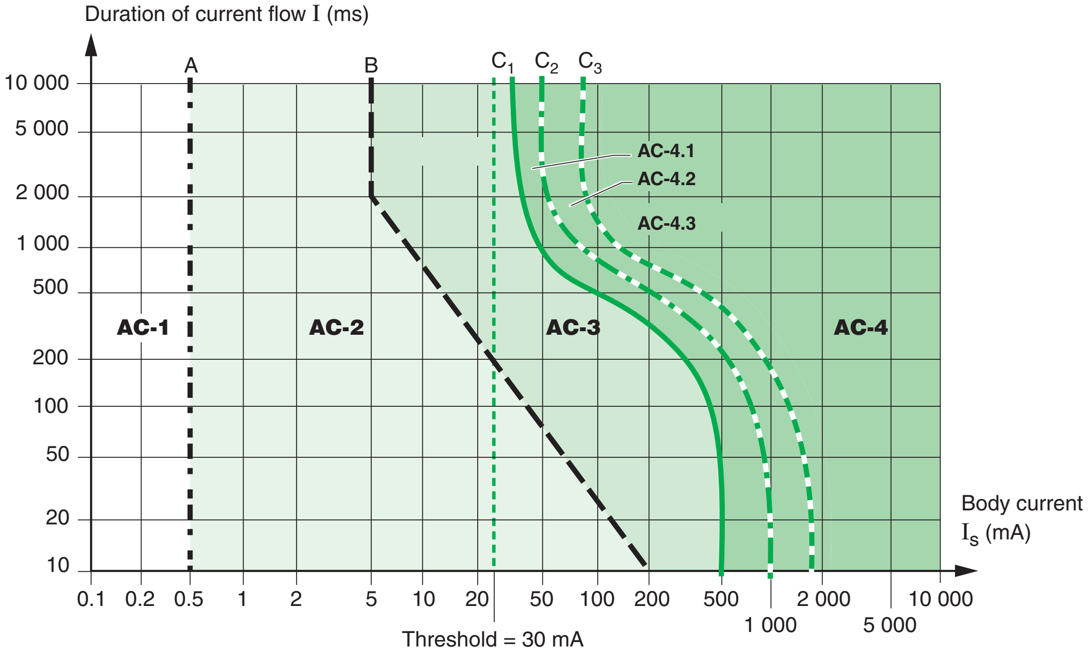
- □ increases up to about 5% between curves C_1 and C_2,
- □ increases up to about 50% between curves C_2 and C_3,
- □ exceeds 50% beyond curve C_3.

The probability of dangerous pathophysiological effects such as cardiac arrest, breathing arrest and severe burns increases with current and time.

Note that a 150 mA current may flow in a person in contact with a 230 V voltage, under unfavourable conditions.

Given the current levels considered dangerous, a maximum permissible value of 30 mA is considered safe.

For LV systems, the dominant component in body impedance is the skin resistance, which



AC-1 : Perception
AC-2 : Involuntary muscular contractions
AC-3 : Difficulty in breathing
AC-4 : Serious pathophysiological effects
    AC-4.1 : probability of ventricular fibrillation increasing up to about 5 %
    AC-4.2 : probability of ventricular fibrillation up to about 50 %
    AC-4.3 : probability of ventricular fibrillation above 50 %

Fig. 2 *: Time/current zones of effects of AC currents (15 Hz to 100 Hz) on persons.*

depends essentially on the environment (dry, humid or wet conditions).

IEC has defined the "conventional touch voltage limit", noted U_L, as the maximum touch voltage that can be maintained indefinitely under the specified environment conditions. The value used is 50 V AC rms. This value is consistent with an average impedance value of 1700 Ω and a maximum current of 30 mA.

Effects as a function of voltage and frequency

IEC 60479-1 provides curves showing the variation in body impedance depending on the voltage and the frequency.

Figure 3 shows that body impedance decreases with frequency. However, note that IEC 60479-2 (Effects of current on human beings and livestock - Special aspects), dealing with the effects of AC current at frequencies above 100 Hz, indicates that the threshold current for ventricular fibrillation at 1000 Hz is approximately 14 times greater than at 50/60 Hz current

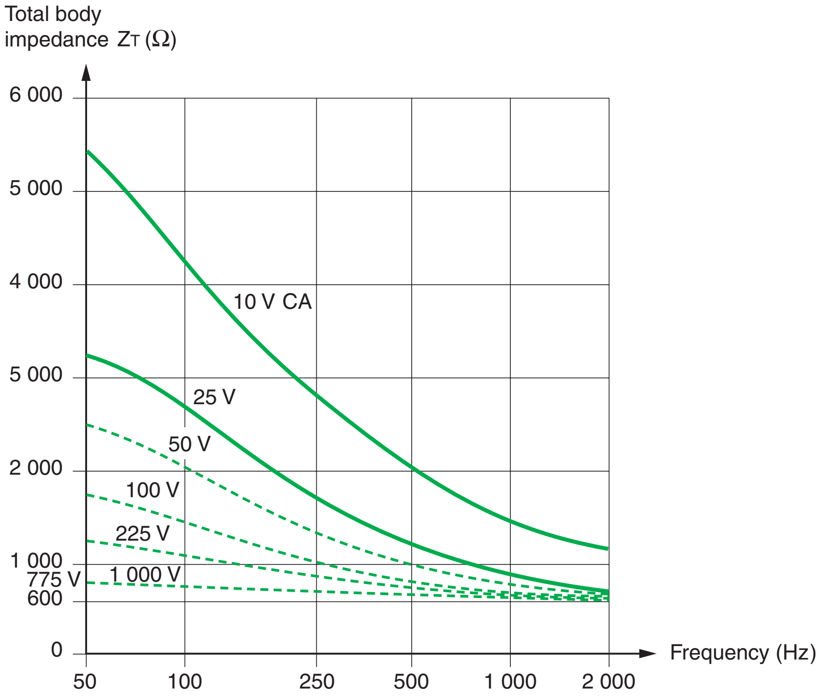


Fig. 3 : Total body impedance Z_T as a function of the frequency and the touch voltage.

2.2 Fire hazards

A study carried out in the 1980s and 1990s in Germany by an insurance company on fires on industrial and commercial premises revealed that electricity was the cause of over 40 % of the fires.

The cause of many electrical fires is a major short-duration temperature rise or electric arc due to an insulation fault. The risk increases with the level of the fault current. It also depends on the level of fire or explosion hazard specific to the room (storage of flammable materials, presence of volatile hydrocarbons, etc.).

Many electrical fires are caused by a combination of factors:

- an old installation,
- wear of insulation,
- accumulation of dust and humidity.

The progressive increase in tracking currents on the surface of polluted and damp insulation results in small discharges that cause carbon deposits. This phenomenon is related to surface condensation and drying cycles and therefore evolves very slowly. If the tracking current exceeds 300 mA, an avalanche phenomenon occurs that can inflame the carbon deposits which, in turn, may inflame the insulation and devices.

A 300 mA leakage current represents a real fire hazard. The leakage current flows from the source to the ECPs, but does not return to the source via the return conductor.

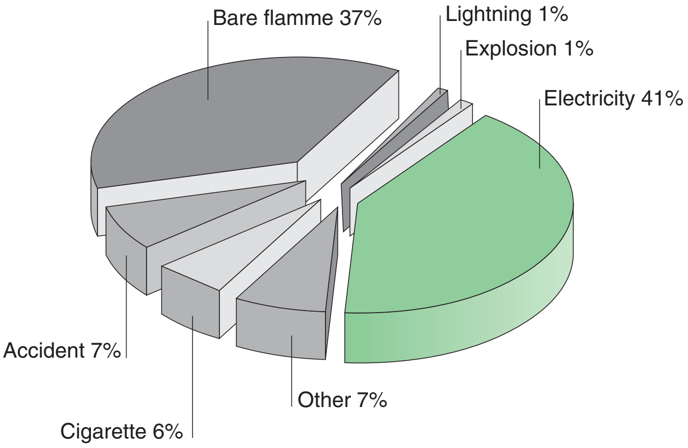


Fig. 4 : Origin of fires in buildings.

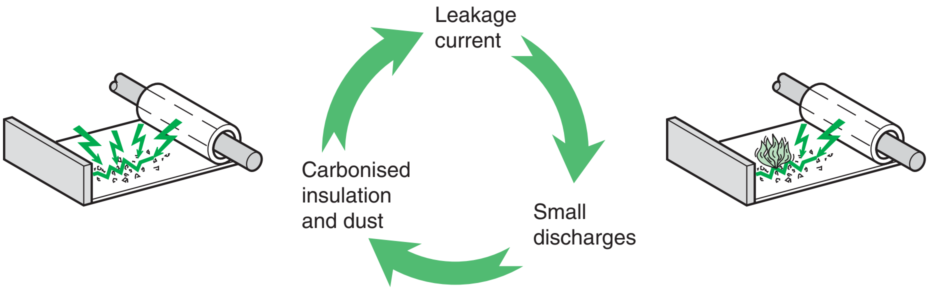


Fig. 5 : Process resulting in a fire.

2.3 Damage to equipment

Certain electrical equipment may be damaged or destroyed by high currents. This is the case for motors during prolonged operation above rated load and cables if too many devices are connected. The overcurrent provokes excessive temperature rise in conductors and may lead to insulation breakdown and the flow of an earth fault current. The latter may remain at a low level, difficult to detect, or rapidly degenerate into a short-circuit and provoke major damage.

3 Protection against the risks of electrical currents

3.1 Installation rules

The international reference standard is IEC 60364, Electrical installations in buildings, and in particular part 4-41, Protection for safety - Protection against electric shock. It lays down installation rules such that dangerous live parts are not accessible and accessible conductive parts are not dangerous under normal and fault conditions.
The standard has been adopted by many countries, as is or with local adaptations. In France for example, low-voltage electrical installations must comply with standard NF C 15-100.

General rules
Installations must be designed to provide general protection against direct contacts during normal operation and additional protection against indirect contacts in the event of a fault.

- General protection is implemented by isolating the live parts, using barriers and enclosures.
Protection in the even of faults is implemented by one or more of the following means:
  - automatic disconnection of the supply,
  - double or reinforced insulation,
  - electrical separation (use of an isolating transformer),
  - use of very low voltage.

Automatic disconnection of supply is the most common solution. It entails certain requirements:
  - earthing of ECPs and equipotential bonding,
  - specification of a maximum disconnection time for a fault (e.g. 0.4 seconds for 230 V).

A protective device must automatically isolate a circuit or device from its supply so that, following a fault between a live part and an ECP of a circuit or device, a touch voltage greater than the conventional limit cannot be present for a time sufficient to create a danger for a person in contact with simultaneously accessible conductive parts.

- Additional protection is required in case the protection against direct contacts fails. In particular, IEC 60364-4-41 requires installation of a device for protection against direct contacts for AC circuits supplying general-usage socket-outlets up to 20 A located outdoors and for socket-outlets up to 32 A used to supply portable equipment intended for outdoor use . The operating threshold of the device must be 30 mA.

System earthing arrangements (SEA)
Standard IEC 60364 defines three main system earthing arrangements (SEA, see **Fig. 6**), used in different manners depending on the country. See Cahiers Techniques publications no. 172 and 173.

They differ according to whether or not the neutral point of the voltage source is earthed and the manner in which the ECPs are earthed. SEA selection depends on installation characteristics and on operating conditions and requirements (environment, monitoring devices, continuity of service).

- TT system

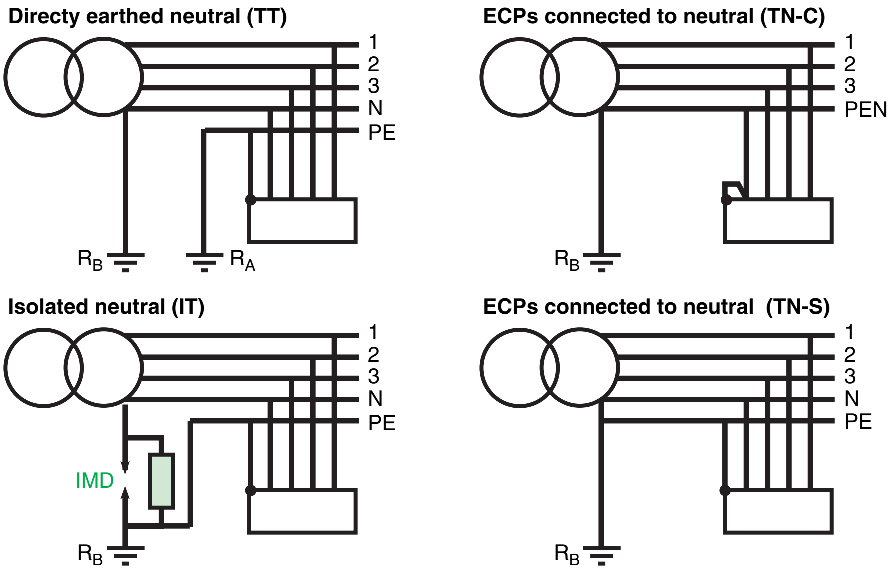
In the TT system:
  - the source neutral is connected to an earth electrode separate from that of the ECPs,
  - all ECPs must be connected to a single earthing system dedicated to the installation.

- TN system

This principle of the TN system is to transform all insulation faults into a phase-to-neutral short-circuit. In this system:
  - the LV neutral point of each source is directly earthed,
  - all ECPs in the installation are earthed, i.e. connected to the neutral by the PE (with separate neutral in TN-S systems) or the PEN (combined with the neutral conductor in TN-C systems) protective conductor.

- IT system

In the IT system, the transformer neutral is:
  - isolated from earth (isolated neutral),
  - or connected to earth via a high impedance (impedant neutral),
  - all installation ECPs are earthed.



IMD: Insulation Monitoring Device

***Fig. 6** : The three main SEAs are the TT, IT and TN systems defined by IEC 60364-1. The TN system may be TN-C (neutral and PE combined) or TN-S (separate neutral and PE).*

3.2 Detection of insulation faults

An insulation fault may be the consequence of insulation deterioration:
- between two live conductors,
- between a conductor and the ECPs or the protective conductor,
- on a single live conductor, making the conductor accessible to touch.

An insulation fault between live conductors becomes a short-circuit.

In all other cases, a fault (in common mode) causes current to flow to earth. This current, which does not flow back via the live conductors, is called the earth-fault current. It is the algebraic sum of the instantaneous values of the currents flowing in the live conductors, hence the name "residual current".

Remark: If the currents are sinusoidal, Fresnel vector representation may be used and it is possible to speak of the "vector sum" of the currents. However this representation is not relevant in the presence of harmonic currents and the term "algebraic sum" is therefore more generally applicable.

This current may be due to an insulation fault between a live conductor and the ECPs (risk of indirect contact) or to a failure of the measures used to insulate or isolate live parts (risk of direct contact). These situations are shown in **figure 7** next page.

The insulation-fault current between a phase and earth (common mode) depends on the type of fault and on the SEA. The current may create a dangerous touch voltage, requiring disconnection of the faulty circuit.

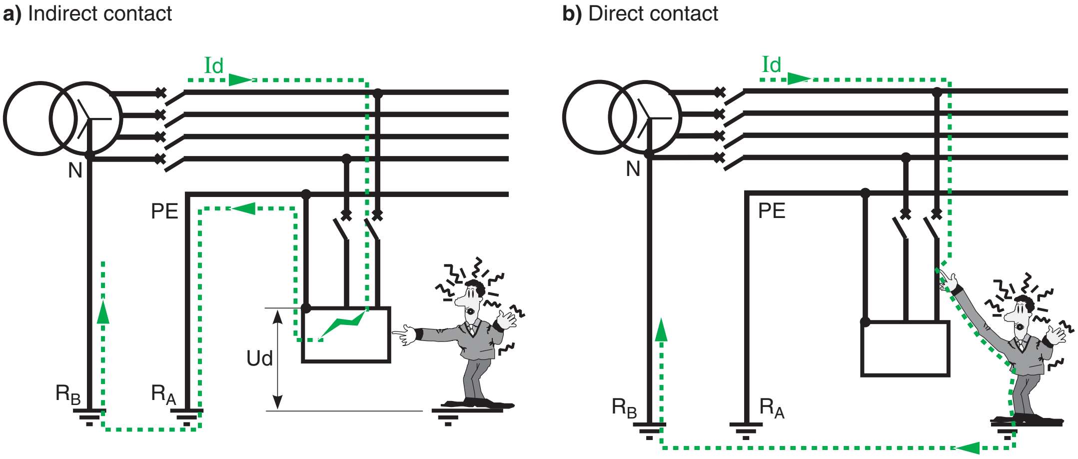
See Appendix 1 for a summary of calculations on fault currents and touch voltages depending on the SEA.

In the TN system, the fault current is equivalent to a short-circuit. The current is high and the circuit can be disconnected by an overcurrent protective device.

In the TT system, however, the current is too low to be detected and cleared by standard overcurrent protective devices (circuit breaker thermal or magnetic protection, fuses).

Similarly, in all cases of direct contact, the fault current is low and cannot be detected and cleared by standard overcurrent protective devices. This is also the case for leakage currents that constitute fire hazards.

Under these conditions, the fault current must be detected and cleared by a special device, i.e. a residual-current device (RCD), discussed in the next section.



a) Indirect contact

b) Direct contact

Fig. 7 : Fault current I_d = residual current.

4 RCD operating principle and description

4.1 Operating principle

The operating principle of an RCD is shown in **figure 8**.

A sensor comprising a toroid that surrounds the conductors detects the algebraic sum of the current in the live conductors (phases and neutral).

The toroid winding detects variations in the flux induced by the residual current.

In the absence of an insulation fault, the algebraic sum of the currents in the conductors is equal to zero and the toroid does not detect any flux.

If an insulation fault occurs, the sum is no longer equal to zero and the fault current in the toroid generates a current in the winding.

This current is rectified, filtered and amplified.

If the resulting signal is greater than a set threshold, a time delay is initiated (it may be equal to zero for an instantaneous response).

If the fault is still present at the end of the time delay, an opening order is issued for a control device.

Use of an RCD is not possible in the TN-C system because the neutral and protective conductors are not separate and the RCD cannot distinguish between the residual and neutral currents.

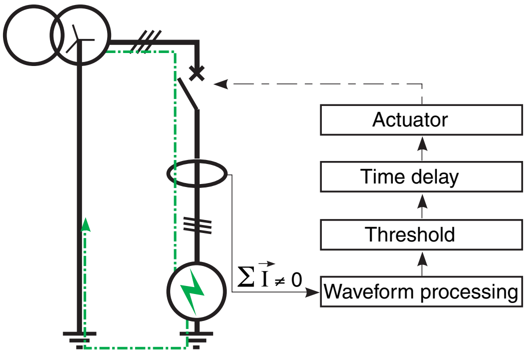


Fig. 8 : Operating principle of an RCD.

4.2 Applications

Additional protection against direct contacts

An RCD can detect low leakage currents that could flow through the body of a person. It thus provides additional protection if the normal protection means fail, e.g. old or damaged insulation, human error, etc. This can also be referred to as ultimate protection because it can interrupt the current even if the other devices have failed.

Use of a 30 mA RCD on all circuits supplying socket-outlets up to 20 A is now mandatory, as per IEC 60364-4-41, Electrical installations in buildings, Protection for safety - Protection against electric shock.

Note that an RCD does not limit the instantaneous current flowing through the body, but does limit the time the current flows. Note also that for a direct contact with a 230 V phase conductor, the flowing current would be approximately 150 mA. RCDs with 10 or 30 mA sensitivities let the same current through.

The two sensitivities provide equivalent protection. However, the 30 mA threshold provides a cost-effective compromise between safety and continuity of service.

Downstream of an RCD, it is possible to supply a number of loads or circuits as long as the leakage current does not trip the RCD. For a given leakage current, a reduction in the threshold makes it necessary to increase the number of protective devices.

Protection against indirect contacts

An RCD is the only solution to protect against indirect contacts on a TT system because the dangerous fault current is too low to be detected by overcurrent protective devices. It is also a simple solution for the TN-S and IT systems. For example, when the supply cable is very long, the low fault current makes it difficult to set the overcurrent protective devices. And when the length of the cable is unknown, calculation of the fault current is impossible and use of an RCD is the only possible solution.

Under these conditions, the RCD operating threshold must be set to somewhere between a few amperes and a several tens of amperes.

Protection against fire hazards
IEC 60364-4-42 (Electrical installations in buildings, Protection for safety - Protection against thermal effects) also recognises RCD effectiveness in protecting against fire hazards by requiring their use with a maximum operating threshold of 500 mA. This threshold should be reduced to 300 mA in the near future, as already recommended by certain national standards such as NF C 15-100 in France.

4.3 Main characteristics

An RCD must be selected taking into account the type of load supplied. This applies in particular to semiconductor-based devices for which fault currents are not always sinusoidal. Examples of semiconductor converters are provided in Appendix 3, with the waveforms of the fault currents and the corresponding type of RCD.

Type AC, A, B

Standard IEC 60755 (General requirements for residual current operated protective devices) defines three types of RCD depending on the characteristics of the fault current.

- Type AC

RCD for which tripping is ensured for residual sinusoidal alternating currents.

- Type A

RCD for which tripping is ensured:

  - for residual sinusoidal alternating currents,
  - for residual pulsating direct currents,
  - for residual pulsating direct currents superimposed by a smooth direct current of 0.006 A, with or without phase-angle control, independent of the polarity.

- Type B

RCD for which tripping is ensured:

  - as for type A,
  - for residual sinusoidal currents up to 1000 Hz,
  - for residual sinusoidal currents superposed by a pure direct current,
  - for pulsating direct currents superposed by a pure direct current,

\- for residual currents which may result from rectifying circuits, i.e.:
\- three pulse star connection or six pulse bridge connection,
\- two pulse bridge connection line-to-line.
with or without phase-angle monitoring, independently of the polarity.

Certain electronic devices can generate fault currents not described above. Examples are provided in Appendix 2. The IEC has begun studies to cover these special cases as well.

Sensitivity

RCD sensitivity is expressed as the rated residual operating current, noted IΔn.
Preferred values have been defined by the IEC, thus making it possible to divide RCDs into three groups according to their IΔn value.

- High sensitivity (HS): 6 – 10 – 30 mA,
- Medium sensitivity (MS): 0.1 – 0.3 – 0.5 – 1 A,
- Low sensitivity (LS): 3 –10 – 30 A.

RCDs for residential or similar applications are always high or medium sensitivity.

It is clear that High Sensitivity (HS) is most often used for direct-contact protection, whereas MS and in particular the 300 and 500 mA ratings are indispensable for fire protection. The other sensitivities (MS and LS) are used for other needs such as protection against indirect contacts (mandatory in the TT system) or protection of machines.

Break time

As indicated in section 1, the effects of electrical currents depend on their magnitude and duration. RCD break times are specified in the product standards:

- IEC 61008, Residual current operated circuit-breakers without integral overcurrent protection for household and similar uses (RCCBs).

- IEC 61009, Residual current operated circuit-breakers with integral overcurrent protection for household and similar uses (RCBOs).
- IEC 60947-2, Low-voltage switchgear and controlgear, Annex B, Circuit-breakers incorporating residual current protection.
- IEC 60947-2, Low-voltage switchgear and controlgear, Annex M, Modular residual current devices - MRCD (without integral current-breaking device).

The standardised break times are indicated in the table of **figure 9** and in the curves in **figure 10** for G and S type devices.

- G (general use) for instantaneous RCDs (i.e. without a time delay)
- S (selective) for RCDs with a short time delay (used in France, for example, for service-connection circuit breakers).

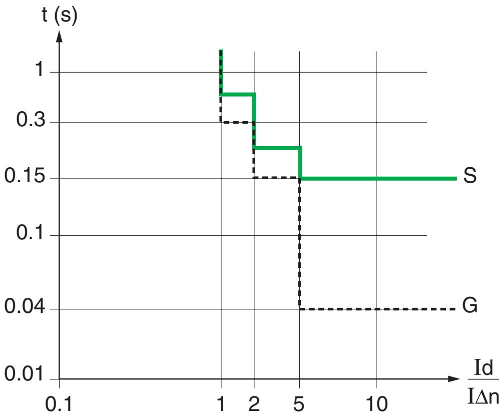


Fig. 10 : Maximum break-time curves for S (selective) and for G (general use) RCDs.

Type	In	IΔn	Standard values of break time (s) and non-actuating time (s) at a residual current (IΔ) equal to:				
	A	A	IΔn	2 IΔn	5 IΔn	5 A, 10 A 20 A, 50 A 100 A, 200 A 500 A	
General	Any value	Any value	0.3	0.15	0.04	0.04	Maximum break times
S	⩾ 25	> 0.030	0.5	0.2	0.15	0.15	Maximum break times
			0.13	0.06	0.05	0.04	Minimum non-actuating times

Fig. 9 : Standardised values of maximum break times and non-actuating times as per IEC 61008.

4.4 Technology

RCD classification depending on supply mode:

"Without auxiliary source" or "Functionally independent of line voltage".

In this type of device, the tripping energy is supplied by the fault current. This highly dependable supply mode is recommended for residential or similar applications where the user is not aware of the dangers of electricity. Many countries, particularly in Europe, recognise the effectiveness of these devices for residential and similar uses (standards EN 61008 and 61009).

"Without auxiliary source" or "functionally dependent on line voltage".

In this type of device, tripping requires an auxiliary source of energy that is independent of the fault current. The source is generally the protected circuit. When the circuit is energised, the RCD is supplied. If there is no voltage, the RCD cannot operate, but there is no danger.

These devices are designed to operate in spite of voltage drops as long as the touch voltage can exceed 50 V (touch voltage limit). This condition is met if a device continues to operate when supplied by only two phases with a voltage drop to 85 V between phases. This is the case for Vigi modules, the RCDs used with Merlin Gerin Compact circuit breakers.

Another distinction for RCDs is whether or not their operation is fail-safe. Two types of devices are considered fail-safe:

- those where tripping depends only on the fault current, i.e. all devices without an auxiliary source are fail-safe,
- those, more rarely used, that automatically trip when conditions can no longer guarantee tripping in the presence of a fault current (e.g. during a voltage drop to 25 V).

Remarks:

IEC 60364-531-2-2-2 indicates that for devices with auxiliary sources that are not fail-safe, "Their use is permitted if they are installed in installations operated by experienced and qualified people".

Standard NF C 15-100, 531.2.2.2 stipulates that they may not be used in household installations or similar applications.

RCDs without auxiliary sources, for which operation does not depend on the supply conditions of the protected circuit, offer high performance and are particularly well suited to high-sensitivity applications in residential installations or for final circuits that must be reset by unqualified persons, for the reasons listed below:

- Final distribution circuits are operated and occasionally installed by unqualified persons (without knowledge concerning the installation or awareness of the risks involved).
- Final circuits are generally single-phase (Ph/N) circuits and occasionally two-phase (Ph/Ph).
- This technique continues to provide protection, even if the neutral or a phase are disconnected upstream of the RCD.
- The devices operate even if the voltage drops to 0 V.
- For additional protection against direct contacts, a high-sensitivity RCD is recognised as

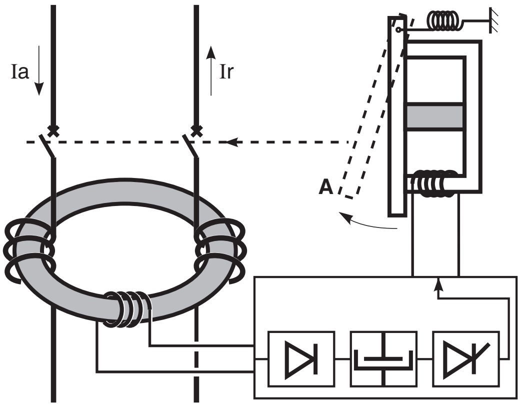


Fig. 11 : The fault current, via the toroid, supplies energy to an electromagnet whose moving part is held by a permanent magnet. When the operating threshold is reached, the electromagnet counterbalances the attraction of the permanent magnet and the moving part, drawn by a spring, opens the magnetic circuit and mechanically actuates circuit-breaker opening.

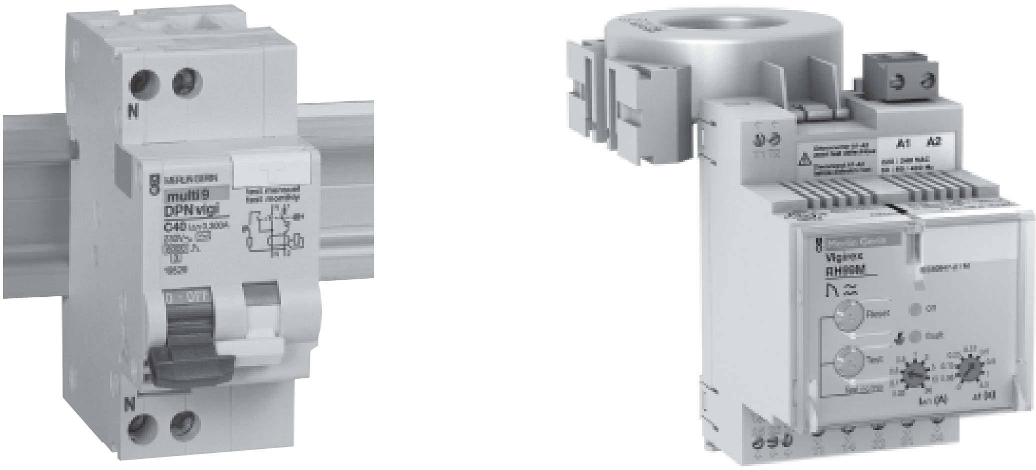


Fig. 12 : Examples of RCDs "without auxiliary source" and "with auxiliary source".

an efficient means if the PE fails (does not exist, is not connected or breaks). This technique offers a further advantage if the earth resistance rises significantly above 500 ohms (old installations, dry periods, corrosion on the earth electrode, etc.) in that certain RCDs with auxiliary sources, connected between a phase and the PE, do not operate correctly under the above conditions.

- This technique is particularly robust given that no electronic components are continuously connected to the distribution system. The result is excellent insensitivity to overvoltages and component ageing. (Electronic components, if present, are connected to the secondary of the zero-sequence current sensor and therefore play a role only if a fault occurs and under very low voltage conditions.)
- This robustness is well suited to installations that are not monitored, generally the case for residential applications.

Operating test

An RCD is a safety device. Whatever the technology used, it must always be equipped with a test system. Although RCDs without auxiliary sources are the most reliable, implementation of fail-safe systems on RCDs with auxiliary sources offers an enhanced degree of safety that does not, however, replace the periodical test.

- Why test RCDs periodically?

In practice, a perfectly fail-safe system, particularly concerning internal faults, does not exist. For this reason, in France, RCDs using auxiliary sources are reserved for industrial and large commercial installations and RCDs without auxiliary sources for domestic and similar installations, which is consistent with their inherent possibilities described above. In all cases, periodical testing is recommended to detect internal faults.

- Principle

For a test, a current is generated that flows in only one of the live conductors surrounded by the toroid, as shown in **figure 13**. The resistor is sized to let through enough current to trip the RCD, taking into account any leakage currents likely to reduce the test current. The maximum permissible value is 2.5 times $I\Delta n$ (for an adjustable device, $I\Delta n$ is the lowest possible setting).

The above principle is very common because it is the means to check the entire system, i.e. toroid, relay and breaking device. It is used on earth-leakage protection socket-outlets and on residual-current circuit breakers with and without integral overcurrent protection. With respect to residual-current relays with separate toroids, the same principle is sometimes used. Certain relays, for example Merlin Gerin Vigirex relays, are equipped with a built-in “test” function and also continuously monitor the continuity of the detection circuit (toroid/relay link and toroid winding).

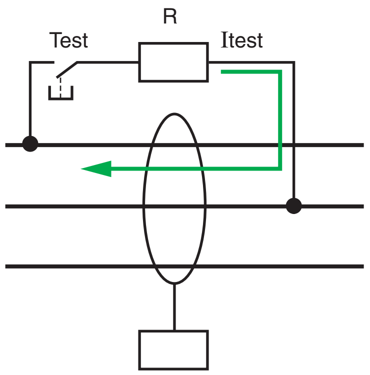


Fig. 13 : Simplified diagram of the circuit for periodical tests.

4.5 Constraints related to the current sensor

The sensor is a toroidal transformer. It surrounds all the live conductors and is therefore excited by the magnetic field corresponding to the algebraic sum of the currents flowing in the phases and neutral. The current induced in the toroid and the electrical signal at the terminals of the secondary winding are therefore proportional to the residual current.

This type of sensor can detect residual currents from a few milliamperes up to several tens of amperes.

Cable with a PE

The basic operating principle of an RCD requires that the sensor surround only the live conductors. The PE protective conductor must therefore be separated from the other conductors, as shown in **figure 14** next page.

Large conductors

Large rectangular sensors are available to measure the residual current of large conductors (see **Fig. 15** next page). Currents should not be summed by using more than one toroid.

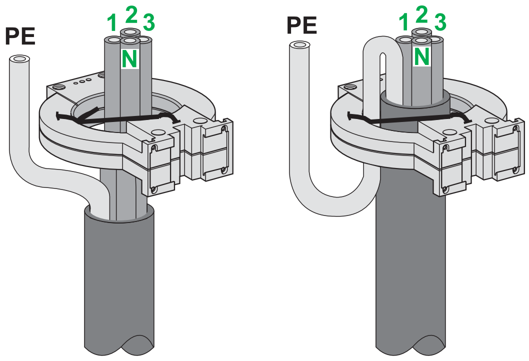


Fig. 14 : Running cables with a PE conductor.

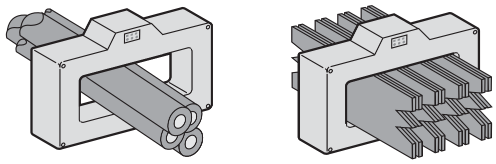


Fig. 15 : Rectangular sensors for large cables or bars

If this difficulty is encountered in a main low-voltage switchboard downstream of the transformer, a toroid may be installed at the head of the installation, on the earthing conductor of the transformer LV neutral point (see **Fig. 16**). According to Kirchhoff's current law, the residual current detected at (N) is identical to that at (G) for a fault occurring in the LV system.

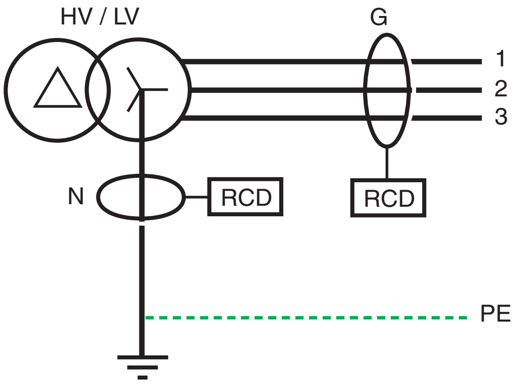


Fig. 16 : Toroid N supplies the same information as toroid G.

High-amperage conductors

To obtain a reliable and linear response from the toroid, the live conductors must be placed as close as possible to its centre to ensure that their magnetic effects compensate for each other perfectly in the absence of residual current. This is because the magnetic field of a conductor decreases proportionally with the distance. In **figure 17**, phase 3 causes local magnetic saturation at point A, i.e. its effect is not proportional. The result is the same if the toroid is positioned near a bend in the cables (see **Fig. 18**). For high currents, parasitic residual induction may result in a signal on the toroid secondary and nuisance tripping. The risk increases when the RCD setting is low with respect to the phase currents, particularly when a short-circuit occurs.

In difficult cases, (e.g. where Iphase max. / IΔn is high), there are two solutions to avoid nuisance tripping:

- use a toroid much larger than necessary, e.g. twice the size required for the conductors,

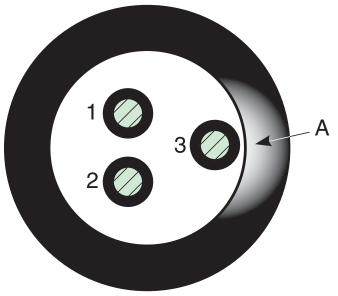


Fig. 17 : Incorrect centering in the toroid causes local magnetic saturation at point A that can result in nuisance tripping.

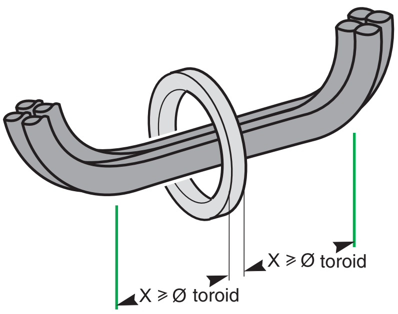


Fig. 18 : The toroid must be installed far enough from bends in cables to avoid nuisance tripping.

- fit a metal sleeve inside the toroid. The sleeve must be made of a magnetic material (soft steel, magnetic sheet metal) (see **Fig. 19**).

When all these precautions are taken, i.e.:

- centering of the conductors,
- toroid oversizing,
- magnetic sleeve,

the ratio Iphase max./$I\Delta n$ can be as high as 50,000.

An RCD with a built-in toroid represents a ready-to-use product for contractors and electricians. The manufacturer carefully designs the complete solution and therefore:

- perfectly centers the live conductors and, for low currents, can design and properly distribute a number of primary turns around the toroid,
- can "operate" the toroid at higher induction to maximise the energy measured and thereby reduce sensitivity to stray induction caused by high currents.

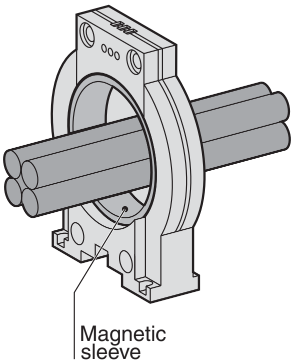


Fig. 19 : A magnetic sleeve positioned around the conductors inside the toroid reduces the risk of tripping due to the magnetic effects of high transient currents.

4.6 Special applications

Discrimination

The goal of discrimination and protection coordination is to ensure that only the faulty part of a circuit is de-energised by tripping of the protective device.

- **"Vertical" discrimination**

This type of discrimination concerns the operation of two protective devices installed in series on a circuit (see **Fig. 20**). Given the tolerances around the RCD thresholds and break times, both current and time discrimination are used.

☐ Current discrimination because, according to standards, an RCD must operate for a fault current between $I\Delta n/2$ and $I\Delta n$. In fact, a factor of 3 is required between the settings of two RCDs to avoid simultaneous operation of the two devices, i.e. $I\Delta n$ (upstream) > 3 $I\Delta n$ (downstream).

☐ Time discrimination for cases where the fault current suddenly exceeds both rated operating currents (see **Fig. 21** next page). It is necessary to take into account the response time, even minimal, of all mechanisms, to which it may be necessary to add deliberate time delays.

The double condition to ensure non-tripping of D_a for a fault downstream of D_b is:

$$I\Delta n\,(D_a) > 3\,I\Delta n\,(D_b) \text{ and } tr\,(D_a) > tr\,(D_b) + tc\,(D_b)$$

$$\text{or } tr\,(D_a) > tf\,(D_b)$$

where:

- tr = non-actuating time

- tc = disconnection time between the instant the operating order is given by the measurement relay to the instant of disconnection (including the arcing time),

- tf = break time, from detection of the fault through to complete interruption of the fault current; tf = tr + tc.

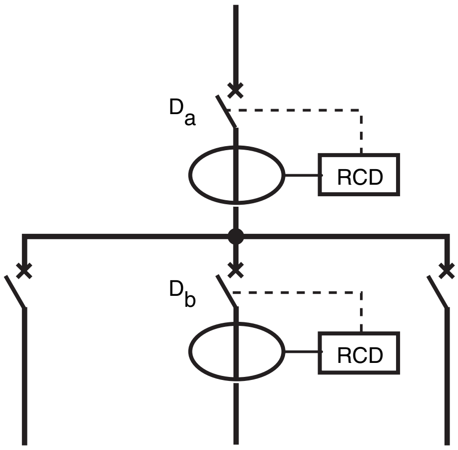


Fig. 20 : Vertical discrimination.

The threshold detection circuits of electronic relays may exhibit a fault memorisation phenomenon. It is therefore necessary to take into account a "memory time", that can be thought of as a virtual increase in the time that a current flows, to ensure that they do not operate after opening of the downstream device.

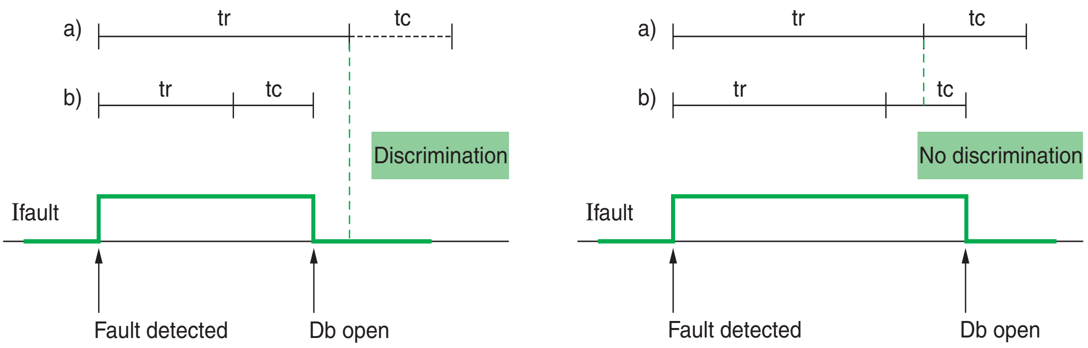


Fig. 21 : *The time delay of an upstream RCD (a) must take into account the non-actuating time tr and the disconnection time tc of the downstream RCD (b).*

Note:

Particular attention must be paid when determining discrimination conditions for circuit-breakers with add-on RCDs and residual-current relays used together (see **Fig. 22**). This is because:

- a circuit breaker with an add-on RCD is defined in terms of the non-actuating time (tr),

- a residual-current relay is defined in terms of the time between the instant the fault occurs and transmission of the opening order, to which it is necessary to add the response time of the breaking device.

It is therefore necessary to calculate the successive tf and tr times (at 2 IΔn, the conventional current for the non-operating test of delayed RCDs) for each RCD, from downstream to upstream.

■ Horizontal discrimination

Sometimes referred to as circuit selection, stipulated in standard NFC15-100, section 535.4.2, it means that an RCD is not necessary in a switchboard at the head of the installation when all the outgoing circuits are protected by RCDs.
Only the faulty circuit is de-energised.

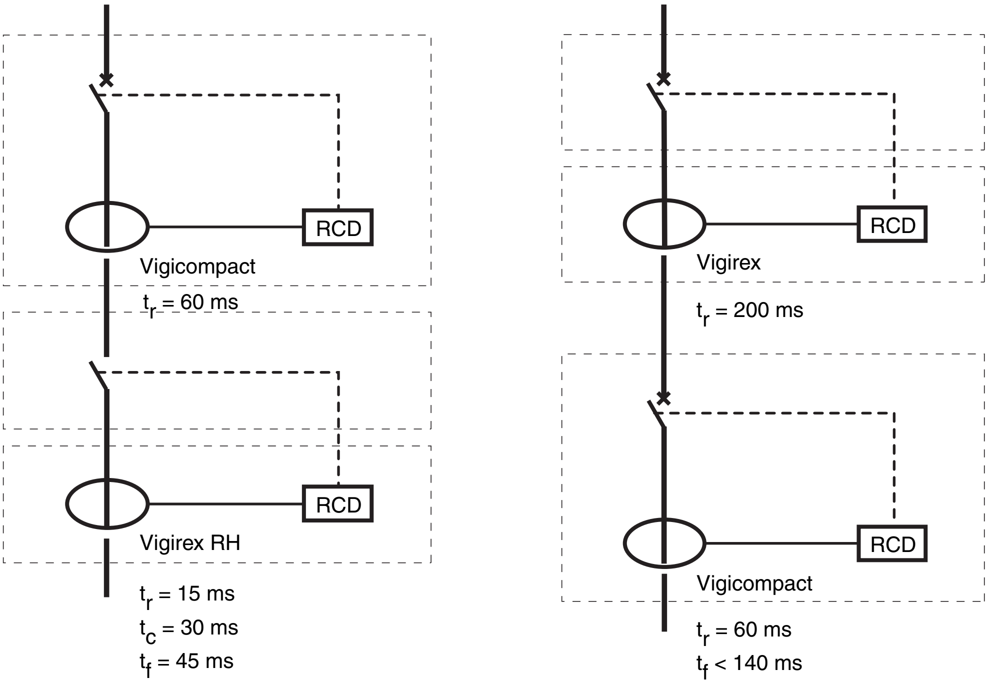


Fig. 22 : *Two examples of time discrimination between a Vigicompact circuit breaker with add-on RCD and a Vigirex relay (Merlin Gerin). Note that these times are much shorter than the authorised actuating times in figure 9.*

The RCDs placed on the other circuits (parallel to the faulty one) do not detect the fault current (see **Fig. 23**).

The RCDs may therefore have the same tr setting.

In practice, horizontal discrimination may present a problem. Nuisance tripping has been observed, particularly on IT systems and with very long cables (stray capacitance in cables) or capacitive filters (computers, electronic systems, etc.). Tripping may occur on non-faulty circuits, as shown in **figure 24**.

Surge arresters

Depending on local utility regulations, RCDs are connected upstream or downstream of surge arresters. If the RCD is placed upstream, it detects the current surge produced by lightning and may trip. A delayed or reinforced-immunity RCD is recommended. If the RCD is downstream, a standard RCD may be used.

Disturbances caused by leakage currents

There are a number of types of leakage currents likely to disturb RCD operation:

- leakage currents at power frequency,
- transient leakage currents,
- high-frequency leakage currents.

These currents may be natural, flowing through the capacitance distributed throughout the cables in the installation, or intentional, i.e. the current flowing through components used intentionally, namely capacitive filters installed on the supply circuits of electronic devices (computers, variable-speed drives, etc.). The purpose of these filters is to bring the devices into compliance with the emission and immunity standards made mandatory by European EMC directives.

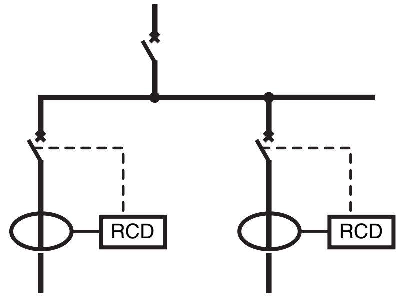


Fig. 23 : Example of horizontal discrimination.

- **Leakage currents at power frequency (50 or 60 Hz)** (see **Fig. 25** next page)

These currents are generated by the supply source and flow through natural or intentional capacitance.

For a single-phase device in a 50 Hz system, continuous leakage currents of approximately 0.5 to 1.5 mA per device are measured. These leakage currents add up if the devices are connected to the same phase. If these devices are connected to all three phases, the currents cancel out when they are balanced (the algebraic sum is equal to zero).

Because of these leakage currents, the number of devices that can be connected downstream of an RCD is limited. See Appendix 3 for a comparison of leakage currents in the different SEAs (TT/TN or IT), which explains why the number of devices that may be connected in an IT system is lower than in the TT or TN systems.

Given that RCD tripping may take place starting at 0.5 IΔn, it is advised, in order to avoid nuisance tripping, to limit the continuous leakage current to 0.3 IΔn for TT and TN systems and to 0.17 IΔn for an IT system.

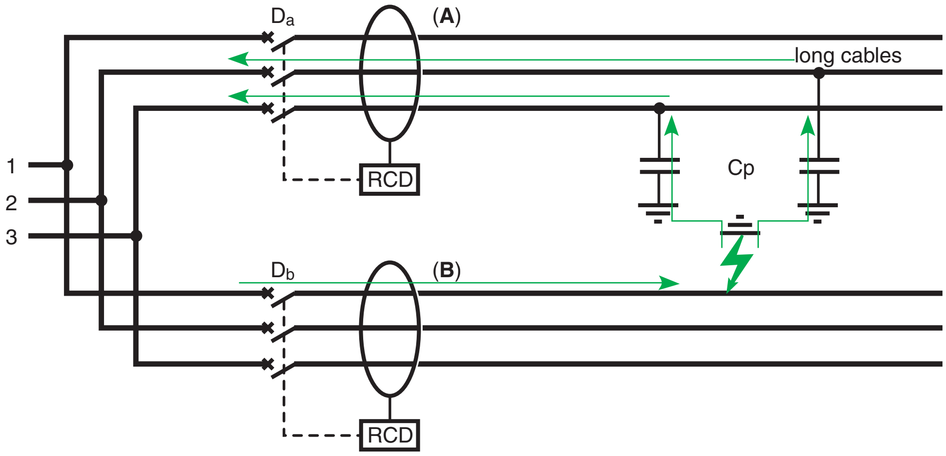


Fig. 24 : In the event of a fault, D_a may open instead of D_b.

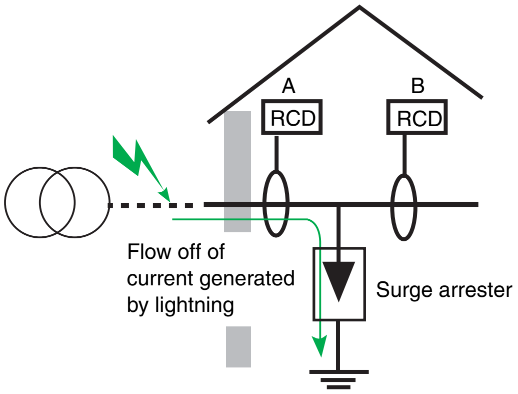


Fig. 25 : Depending on local regulations, in an installation containing a surge arrester, the RCD may be placed at A (S-type or immunised RCD) or at B (standard RCD)

Use of an RCD with a narrow operating range (0.7 IΔn to IΔn) reduces this constraint.

A narrow operating range is available from "si" (super-immunised) or Vigirex RCDs from Merlin Gerin.

■ **Transient leakage currents**

These currents appear when energising a circuit with a capacitive unbalance or during a common-mode overvoltage (see **Fig. 26**).

For example, measurements carried out when starting a workstation equipped with a capacitive filter revealed a transient leakage current with following characteristics:

- ☐ amplitude of the first peak: 40 A
- ☐ oscillation frequency: 11.5 kHz
- ☐ damping time (66 %): 5 periods

RCDs with a certain non-actuating time avoid nuisance tripping caused by this type of waveform. Examples are "si" type RCDs (IΔn = 30 mA and 300 mA), Vigirex and S-type RCDs (IΔn ≥ 300 mA).

■ **High-frequency leakage currents**

High-frequency leakage currents (a few kHz up to a few MHz) are caused by the chopping technique used by variable-speed drives or the electronic ballasts of fluorescent lighting. Certain conductors are subjected to high voltage gradients (approx. 1 kV/μs), which generate major current spikes through the stray capacitance of circuits.

Leakage currents of a few tens or hundreds of mA can flow (common mode) and be detected by the RCD, as shown in **figure 27** for a variable-speed drive.

Unlike the 50 Hz - 60 Hz leakage currents for which the algebraic sum is zero, these HF currents are not synchronous over all three phases and their sum constitutes a non-negligible leakage current.

In order to prevent nuisance tripping, RCDs must be protected against these HF currents (equipped with low-pass filters). This is the case for industrial RCDs of the Vigirex range and for the Merlin Gerin “S”, “A si” and “B” type RCDs.

Variable-speed drives

For combinations of RCDs and variable-speed drives using frequency conversion, it is necessary to simultaneously take into account a number of constraints:

- ■ leakage currents when energising,
- ■ continuous leakage currents at 50/60 Hz,
- ■ continuous HF leakage currents,
- ■ special current waveforms for faults at the drive output,
- ■ current with a DC component for faults on the DC bus.

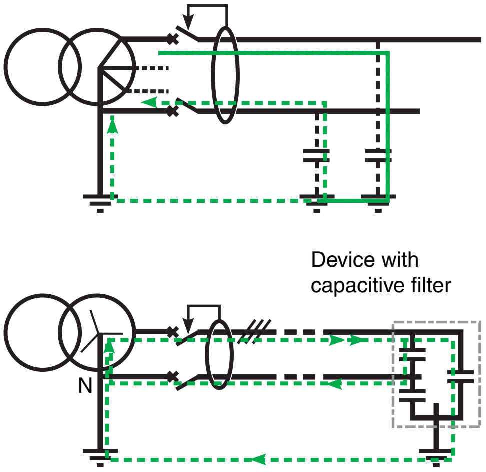


Fig. 26 : Leakage current caused by the capacitance distributed throughout the cables or flowing through the input capacitors of devices (dotted lines).

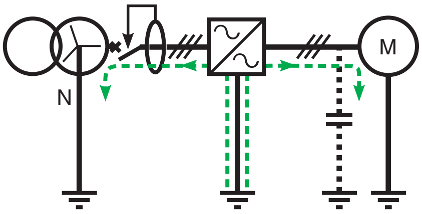


Fig. 27 : RCD disturbance caused by high-frequency leakage currents.

An analysis of these phenomena and solutions to satisfy the constraints are presented in detail in Cahier Technique publication no. 204, LV protection devices and variable-speed drives.

See also Appendix 2, Types of converters and fault-current waveforms.

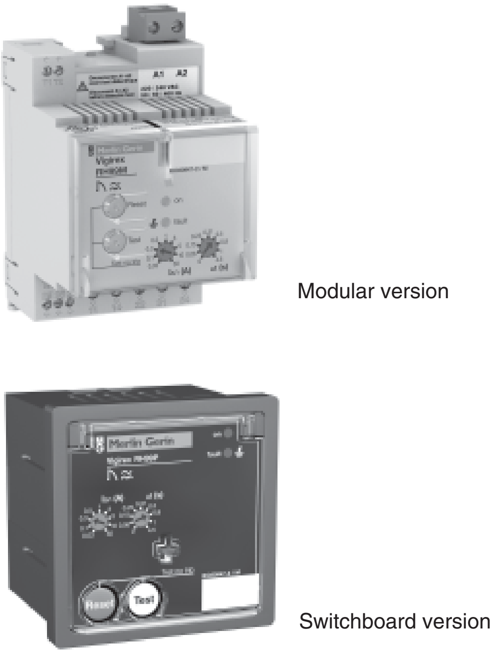
Uninterruptible Power Supplies (UPS)

In installation with backup sources such as UPSs, the protection system must take into account the different possible configurations. In particular operation on AC power or on the batteries, bypass switches closed or not, etc.

In the example in **figure 29**, the installation (TT system) includes a UPS. If AC power fails, it is necessary to earth the neutral downstream of the UPS (i.e. close contactor K) to ensure correct operation of the RCDs.

However, this earthing operation is not indispensable to protect persons because:

- the installation becomes an IT system and the first fault is not dangerous,
- the probability of a second insulation fault occurring during the limited time of operation on battery power is very low.


Modular version

Switchboard version

Fig. 28 : RCDs with HF-current filtering (Vigirex RH99M and RH99P from Merlin Gerin.

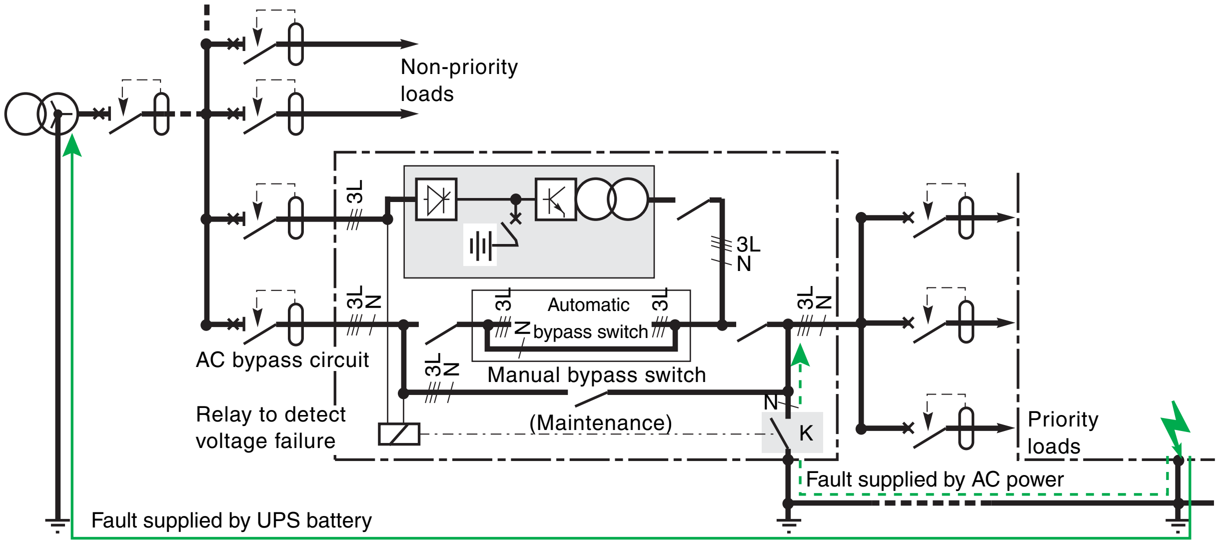


Fig. 29 : When loss of AC power is detected, contactor K closes to recreate the TT system downstream of the UPS.

5 Conclusion

At a time when electricity has come to play an increasingly dominant role in residential, commercial and industrial applications, it is useful to review and quantify electrical hazards and provide information on residual-current devices (RCD).
As for all devices, they have their strong and weak points. Not yet fully perfected, they nonetheless play an increasingly important role in the protection of life and property. All industrialised countries make extensive use of RCDs, with a variety of system earthing arrangements, in both industry and housing.
The following are the most important points to be retained from installation standards and current practice.

■ For the protection of persons against direct contacts, an RCD is not only very useful, but often an additional measure required by standards, whatever the SEA. It is the ultimate line of defence in the protection of human life.

■ For the protection of persons against indirect contacts, an RCD is:

□ compulsory for the TT system,

□ necessary for the IT system if there are several earth electrodes,

□ recommended for very long circuits on TN and IT systems.

■ RCDs also provide protection against:

□ fires of electrical origin. They are the only effective means to limit fire hazards caused by tracking currents, whatever the SEA,

□ destruction of machines in the TN system.

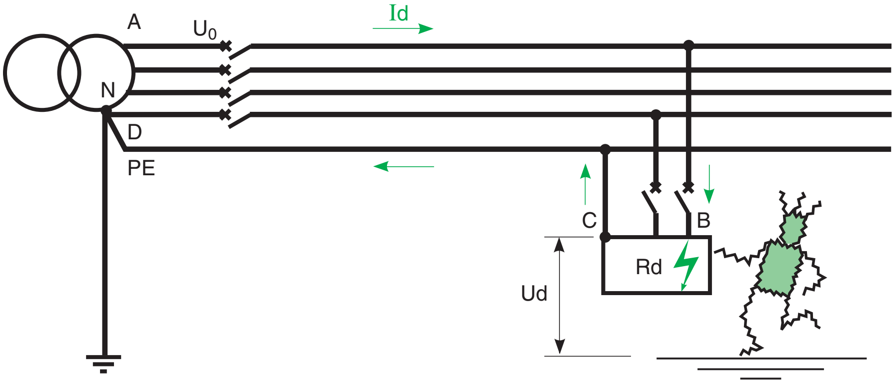
Modern RCDs continue to progress in terms of reliability and immunity to interference phenomena that are not insulation faults.
The purpose of this document is to further knowledge of RCDs and thereby contribute to the safety of life and property.

Appendix 1: calculation of touch voltages

This section indicates briefly how touch voltages due to insulation faults are calculated, depending on the SEA.

For more information, see Cahier Technique publication no. 172, Earthing systems in LV.

TN system



$$Ud = \frac{0.8\ U_o}{2} \text{ if } R_{PE} = R_{ph} \text{ and } Rd = 0$$

$$Id = \frac{U_o}{R_{AB} + Rd + R_{CD}} \Rightarrow \frac{0.8\ U_o}{R_{ph} + R_{PE}}$$

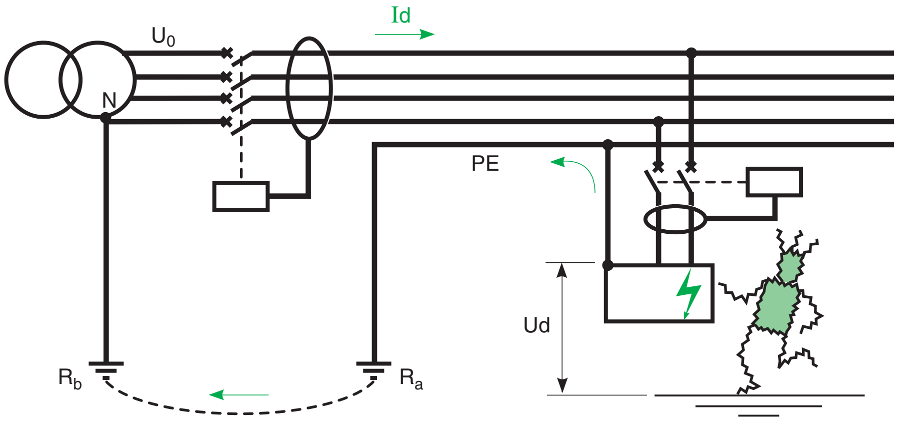
In a 230/400 V system, the touch voltage Ud is therefore 92 V. This voltage is greater than the conventional touch voltage limit U_L and represents a danger, i.e. the circuit must open.

In general, given the level of the fault current Id, opening can be initiated by the overcurrent-detection devices.

When the resistance values R_{ph} and R_{PE} are high or unknown, RCD protection is required.

Fig. 30 : Touch voltage for insulation faults on a TN system.

TT system



$$Id \approx \frac{U_o}{R_a + R_b} \qquad Ud = U_o \frac{R_a}{R_a + R_b}$$

In a 230/400 V system, the touch voltage is approximately 115 V (if $R_a = R_b$). This voltage is greater than the conventional touch voltage limit U_L and represents a danger, i.e. the circuit must open.

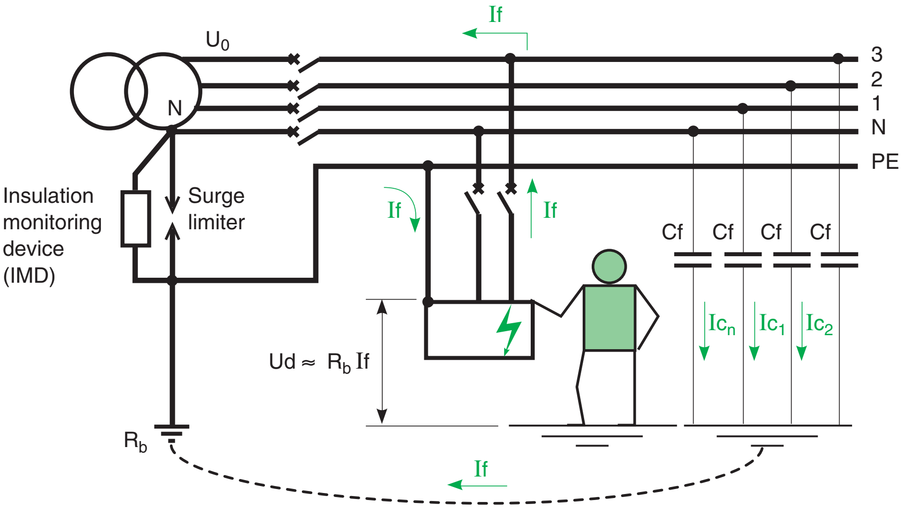
If the earth resistance is approximately 10 Ω, the fault current is approximately 11 A.

In general, opening cannot be initiated by the overcurrent-detection devices.

Use of an RCD is therefore mandatory.

Fig. 31 : Touch voltage for insulation faults on a TT system.

IT system



Even with high leakage capacitances of approximately 1 μF, the leakage current If for the first fault is less than 0.1 A.

The result is a harmless touch voltage of approximately one volt. Disconnection is not necessary for the first fault.

If a second fault occurs, the situation is that of the TN system.

Fig. 32 : Touch voltage for insulation faults on an IT system.

Appendix 2: types of converters and fault-current waveforms

Standard EN50178 (Electronic equipment for use in power installations) indicates the types of RCD to use in combination with different semiconductor assemblies. It also indicates the corresponding fault-current waveforms.

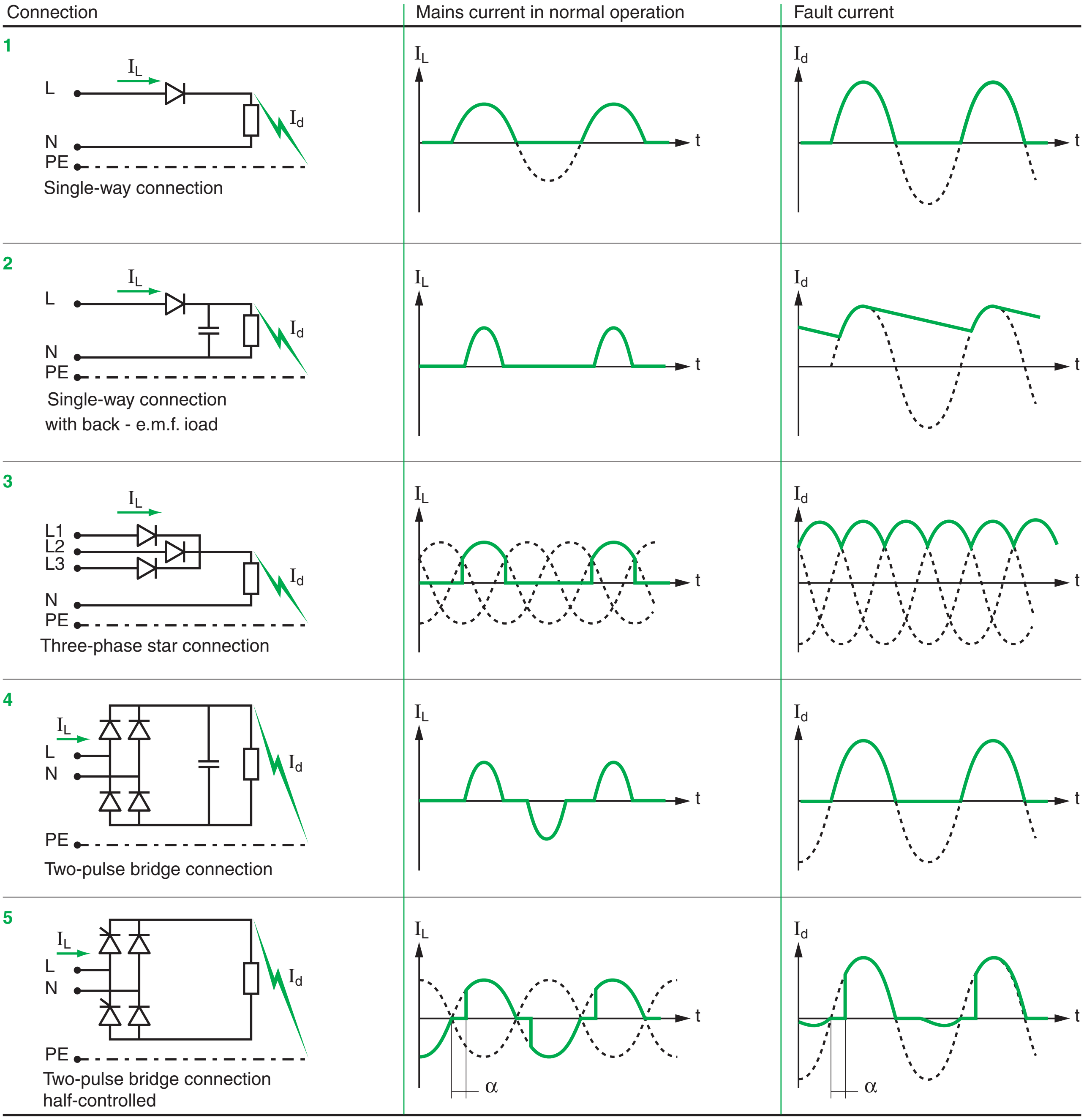


Fig. 33 : Fault currents corresponding to different semiconductor assemblies (continuation p. 26).

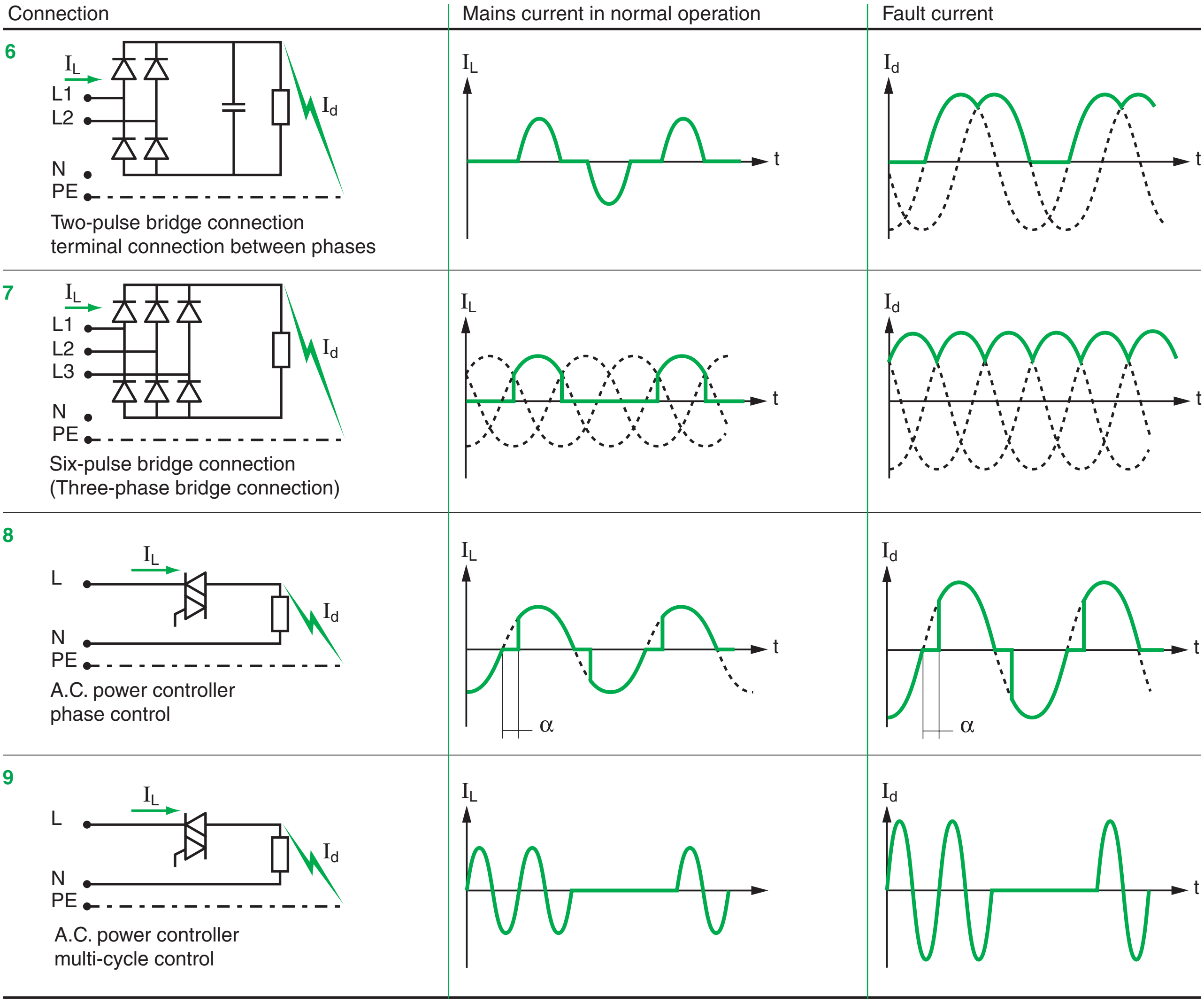


Fig. 33 (continuation of page 25) : Fault currents corresponding to different semiconductor assemblies.

Circuits no. 8 and 9 must be protected by type AC, A or B RCDs.

Circuits no. 1, 4 and 5 must be protected by type A or B RCDs.

Circuits no. 2, 3, 6 and 7 must be protected by type B RCDs.

Examples of loads requiring type A or B RCDs:

■ Equipment with single-phase diode rectifiers (circuit no. 4)

□ Examples include pumps, fans, air-conditioners, lifting and handling equipment, lifts, packing machines, special machines (textile, machine tools, etc.).

Power ratings are 0.37 to 2.2 kW for 230 V/50 Hz (for higher ratings, the supply is generally three-phase).

An insulation fault is possible if a braking resistor is connected to the DC circuit (DC bus). An internal insulation fault is highly unlikely.

□ Power supplies for DC circuits

Examples include welding equipment, battery chargers, electronic devices (PLCs, regulators, telephone exchanges, etc.), excitation windings of DC motors, electromagnet coils.

The maximum power rating is 3 kW (for higher ratings, the supply is generally three-phase).

Remark. Most of the time, these devices have an isolating transformer upstream of the rectifier. In this case, an insulation fault between the DC circuit and earth does not cause a fault current. It is thus possible, for example, to operate with one battery pole earthed.

□ Switch-mode power supplies

Examples include computer hardware, stereo and video equipment, etc.

■ Equipment with single-phase SCR rectifiers (circuit no. 5)

□ Variable-speed drives for DC motors

This technique has been largely replaced by frequency converters, but still exists.

Power ratings are less than 10 kW.

□ Battery chargers

This type of rectifier is used for certain battery chargers, however an isolating transformer is generally installed upstream of the rectifier. Consequently, there is no residual current if a fault occurs downstream of the rectifier.

Other types of equipment with non-sinusoidal fault currents

■ Frequency converters with a single-phase power supply

The input circuit is a circuit no. 4. For a fault on the DC circuit, a type A RCD is suitable.

The current waveform for a fault on the output of a single-phase frequency converter is shown in **figure 34**. This waveform is not described by present standards. The IEC has begun studies to cover these special cases as well. Even if this current does not correspond to the waveform indicated for type A RCDs, the type A RCDs from Merlin Gerin provide protection.

■ Frequency converters with a three-phase supply

The input circuit is a circuit no. 7 and requires a type B RCD.

The current waveform for a fault on the output of a 3-phase frequency converter is shown in **figure 35**.

A type B RCD is perfectly suited. If there is no risk of a fault on the DC bus, a type A RCD is also suitable, even if this type of fault current does not correspond to the waveform indicated for type A RCDs.

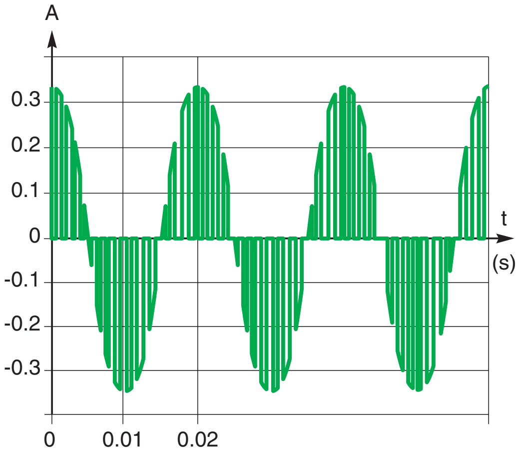


Fig. 34 *: Fault current at the output of a single-phase frequency converter.*

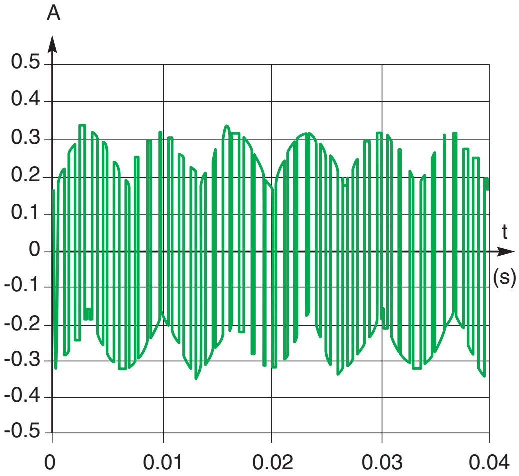


Fig. 35 *: Fault current at the output of a three-phase frequency converter.*

Appendix 3: leakage currents for different system earthing arrangements

Difference between zero-sequence currents in TT/TN and IT systems

Consider the simplified diagram of a device supplied by a phase and neutral, in the TN system. The capacitors C are connected between the live conductors and earth to make the device immune to power system disturbances.

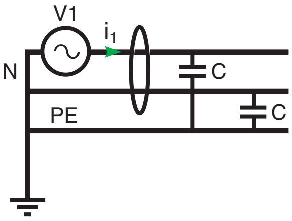


Fig. 36 : Device connected to a TN system.

The current measured by the RCD is equal to:

$i1 = V1\ C\ \omega$

For an IT system, if the first fault is assumed to occur on phase 2, the simplified diagram is that shown below.

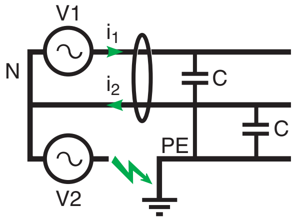


Fig. 37 : Device connected to an IT system.

The current measured by the RCD is equal to:

$i_T = i_1 - i_2$

where $i_1 = (V_1 - V_2)\ C\ \omega$

$i_2 = V_2\ C\ \omega$

What is more, it is clear that:

$V_1 = V \sin\omega t$

$V_2 = V \sin(\omega t - \frac{2\pi}{3})$

Calculation of i_T:

$i_T = i_1 - i_2 = (V_1 - 2V_2)\ C\ \omega$

$$i_T = V\ C\ \omega\left[\sin\omega t - 2\sin\left(\omega t - \frac{2\pi}{3}\right)\right]$$

$$i_T = V\ C\ \omega\left[\sin\omega t - 2\left(\sin\omega t \cos\frac{2\pi}{3} - \sin\frac{2\pi}{3}\cos\omega t\right)\right]$$

$$i_T = V\ C\ \omega\ 2\left(\sin\omega t + \frac{\sqrt{3}}{2}\cos\omega t\right)$$

This expression can be written as:

$i_T = V\ C\ \omega\ 2\ a\ (\cos\alpha \sin\omega t + \sin\alpha \cos\omega t)$

$i_T = V\ C\ \omega\ 2\ a \sin(\omega t + \alpha)$

where identication gives:

$a \cos\alpha = 1$

$$a \sin\alpha = \frac{\sqrt{3}}{2}$$

hence: $a^2\left(\cos^2\alpha + \sin^2\alpha\right) = 1 + \frac{3}{4}$

As a result: $a = \frac{\sqrt{7}}{2}$

$i_T = V\ C\ \omega\ \sqrt{7}\sin(\omega t + \alpha)$

The absolute value of the leakage current is $\sqrt{7} \approx 2{,}6$ times higher for the first fault on an IT system than on a TN system.

There is therefore a risk of nuisance tripping for the first fault in the IT system, i.e. it is necessary to reduce the number of devices monitored by each RCD, compared to the number possible in the TN system. (See the table below).

Limitation of the number of devices monitored by each RCD:

Load made up of computers.

Max nb of loads per 30 mA "si" RCD	**TT**	**TN-S**	**IT**
Office PC *	6	4	2
Workstation **	3	2	1

*: Includes the PC, a monitor and a laser printer

**: Includes the computer with extensions, a large monitor and a laser printer.

For smaller configurations, the number of loads can be increased.

Load made up of lamps with electronic ballasts:

Max nb of ballasts per si RCD	**TT**	**TN-S**	**IT**
300 mA	300	220	100
30 mA	30	22	10

Appendix 4: RCD thresholds and power system voltages

In the United States, certain circuits supplying socket-outlets and not equipped with a PE conductor are protected by a GFCI (ground-fault circuit interrupter) which is a residual-current device. This is required by article 210-8 of NEC, 680-10, 511-10. If residual-current protection is provided, it is built into the socket-outlets and the sensitivity used is 5 mA.

The decision to use a sensitivity of 5 mA (± 1 mA) is not discussed anywhere in detail, however a number of factors explain the decision.

Note that 120 V distribution in the TN-S system significantly reduces the risks. If a solid insulation fault occurs in a device and if the resistance of the phase conductors (size, length) is equivalent to that of the return conductors (PE or metal conduit), the touch voltage of the exposed conductive parts (ECPs) on the faulty device is equal to approximately half the phase voltage, i.e. 60 V.

This 60 V voltage is close to the 50 V voltage recognised as being not dangerous (conventional touch voltage limit). Consequently, the standardisation organisation in the USA considers that given the characteristics of LV distribution in North America, additional protection against direct contacts is not as necessary as in three-phase 230/400 V systems where the touch voltage of the ECPs of a faulty device is twice as high.

This explains why, in the USA, protection against direct contacts is not mandatory on switchboards, but only on the socket-outlets of certain circuits.

For direct contact with a conductor, e.g. a damaged extension cord, the touch voltage in the USA is 120 V. The impedance of the human body at 120 V is higher than at 230 V and amounts to approximately 2200 Ω (median value). The current that would flow in the body would therefore be 120 V/2200 Ω = 54.5 mA.

A 30 mA RCD would operate in 300 ms for a current of 54.5 mA ($< 2\ I\Delta n$) according to the actuating-time tables in the IEC standards. The person in question would be severely affected by a current flowing through the body for this relatively long time.

In a system with a 120 V phase-to-neutral voltage, a 5 mA RCD is therefore better because the tripping time for the same 54.5 mA current ($> 5\ I\Delta n$) is only 40 ms. In this case, tripping is as fast as a 30 mA RCD on a 230 V system.

The 5 mA sensitivity used in the USA for protection against direct contacts in socket-outlets would therefore appear suitable for the two-phase TN-S systems (240 V phase-to-phase) used in the USA.

For a three-phase system (230 V phase-to-neutral), the 30 mA sensitivity is better suited to provide protection against direct contacts, with devices installed in switchboards or, where applicable, in socket-outlets.

Appendix 5: Bibliography

Reference documents:

- IEC 60364, Electrical installations in buildings
- IEC 60479-1, Effects of current on human beings and livestock - Part 1. General aspects
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- IEC 61008, Residual current operated circuit-breakers without integral overcurrent protection for household and similar uses (RCCBs)
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Other publications

- Electrical installation guide
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