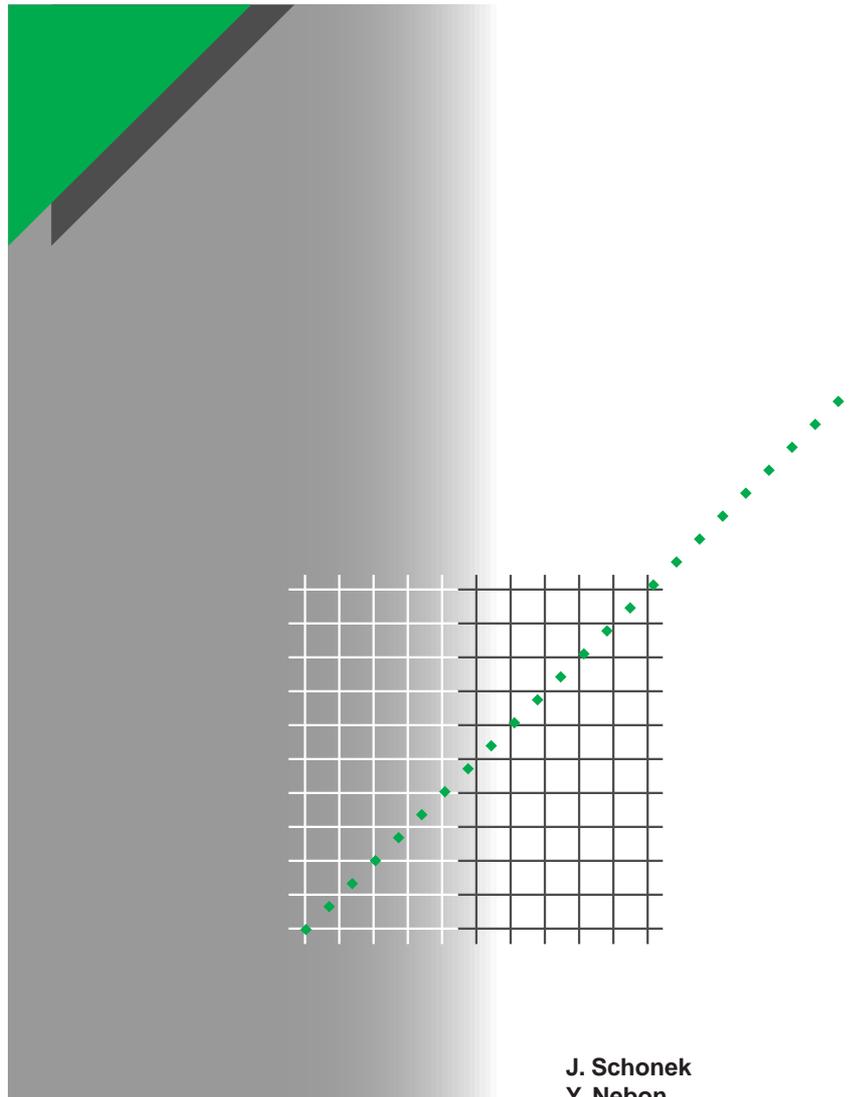


Cahier technique no. 204

LV protection devices and variable speed drives (frequency converters)



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no. 204

LV protection devices and variable speed drives (frequency converters)



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LV protection devices and variable speed drives (frequency converters)

The purpose of this “Cahier Technique” is to explain the specific phenomena observed in LV installations when there is an overload or electrical fault in circuits equipped with variable speed drives. Various recommendations are given to ensure that persons and property are protected, and to provide optimum continuity of service.

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1 Frequency converter type variable speed drives for asynchronous motors

1.1 Description

Purpose

The purpose of “frequency converter” type variable speed drives is to supply 3-phase asynchronous motors in such a way as to obtain operating characteristics which are radically different from those obtained in normal use (motors supplied directly from the power supply), with constant amplitude and frequency. The table in [figure 1](#) lists the advantages of these devices.

Principle

This consists of supplying the motor with a voltage wave with variable amplitude and frequency, while keeping the **voltage/frequency ratio more or less constant**.

This voltage wave is generated by an electronic power device whose simplified schematic is shown in [figure 4](#).

Asynchronous motor	... in normal use	... with variable speed drive
Starting current	Very high, around 6 to 8 times the nominal current in rms value and 15 to 20 times in peak value	Limited in the motor (in general: around 1.5 times the nominal current)
Starting torque T_s	High and not controlled, around 2 to 3 times the nominal torque T_n	Around 1.5 times the nominal torque T_n and controlled for the whole of the acceleration
Starting	Sudden: its duration only depends on the characteristics of the motor and the driven load (resistive torque, inertia)	Smooth, gradual and controlled (for example, linear speed ramp)
Speed	Varies slightly according to the load (close to the synchronous speed N_s)	Variation possible from zero up to a value greater than the synchronous speed N_s
Maximum torque T_m	High, around 2 to 3 times the nominal torque T_n	High, available across the whole speed range (around 1.5 times the nominal torque)
Electrical braking	Relatively complex, requiring protection devices and a special schematic	Easy
Reversing	Easy only after the motor has stopped	Easy
Risk of stalling	Yes, with overtorque (resistive torque $> T_m$), or if voltage drops	No
Motor operation in the torque-speed plane	See fig. 2	See fig. 3

Fig. 1 : comparison of the operating characteristics, showing the advantages of “frequency converter” type variable speed drives.

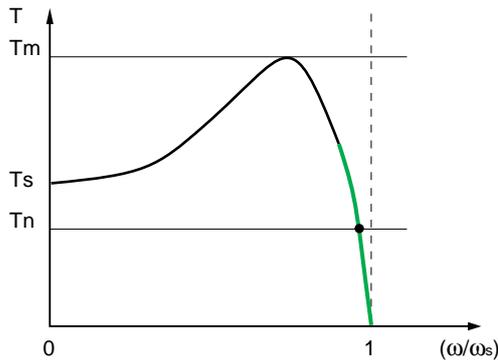


Fig. 2 : speed-torque diagram for a motor supplied directly. The operating zone of the motor in the torque-speed plane is limited to the green part of the curve.

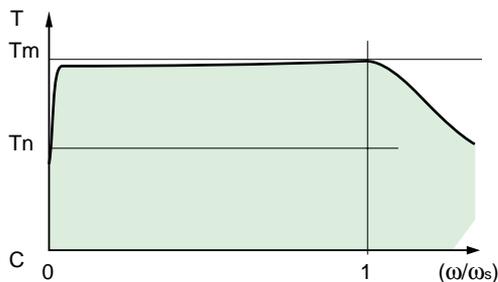


Fig. 3 : speed-torque diagram for a motor supplied via a frequency converter. The operating zone of the motor in the torque-speed plane is shown in green.

The converter consists of:

- a single-phase or 3-phase diode rectifier bridge combined with a capacitor, forming a DC voltage source (DC Bus),
- an inverter bridge, generally with IGBTs (Insulated Gate Bipolar Transistors), supplied with a DC voltage, which generates an AC voltage wave with variable amplitude and frequency using the “Pulse Width Modulation” (PWM) technique,
- a control unit providing the conduction commands to the IGBTs according to instructions given by the operator (run command, direction of operation, speed

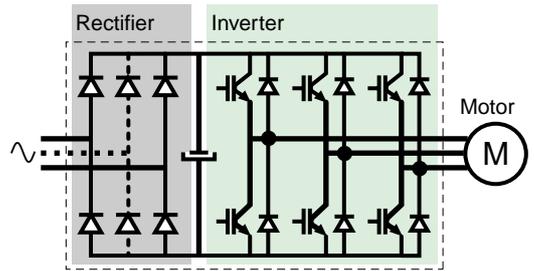


Fig. 4 : simplified schematic of a frequency converter.

reference, etc) and the measurement of the electrical values (line voltage, motor current). The PWM principle used in the inverter bridge consists of applying a series of voltage pulses to the motor windings, whose amplitude is equal to the DC voltage supplied by the rectifier. The width of the pulses is modulated so that a variable amplitude AC voltage is created. The curves shown in **figure 5** are examples of phase-to-phase voltage and of current in one of the machine windings (assuming delta-connected windings).

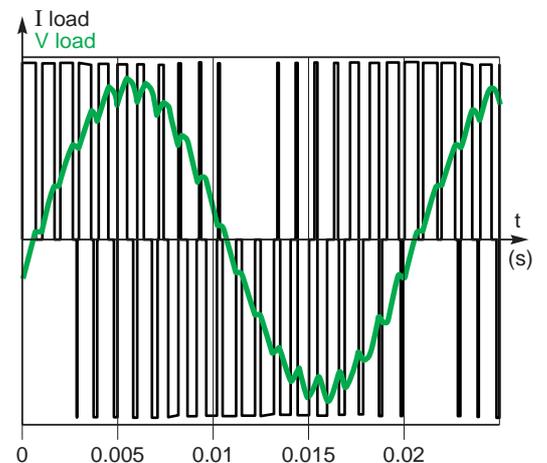


Fig. 5 : voltage with PWM and current in a machine winding.

Characteristics of the current drawn by the drive

■ Waveform

□ In the case of a 3-phase power supply
The rectifier bridge combined with the filter capacitor draws a non-sinusoidal current from the line supply. The shape of this current is shown in **figure 6** and its harmonic spectrum is shown in **figure 7** .
The typical harmonic distortion value THD is 40%.
It should be noted that this distortion is obtained by adding line chokes that cause a voltage drop of between 3 and 5%. In the absence of these

line chokes, the current distortion is higher: it can reach 80% if there is no inductance in the drive.

□ In the case of a single-phase power supply
The current drawn is shown in **figure 8** and its spectrum in **figure 9** .

The typical harmonic distortion value THD is 80%.

It should be noted that this distortion is again obtained by adding a line choke that causes a voltage drop of between 3 and 5%. In the absence of this line choke, the current distortion is higher: it can exceed 100% if there is no inductance in the drive.

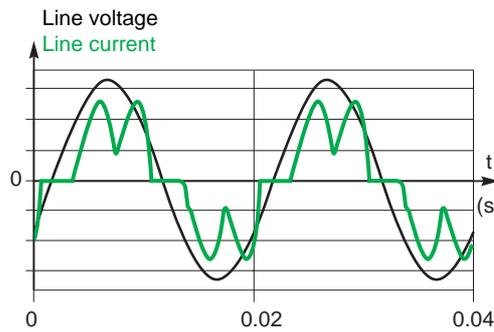


Fig. 6 : current drawn and phase voltage of the line supply (3-phase supply).

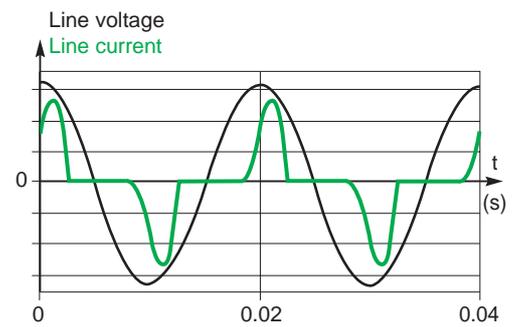


Fig. 8 : current drawn and phase voltage of the line supply (single-phase power supply).

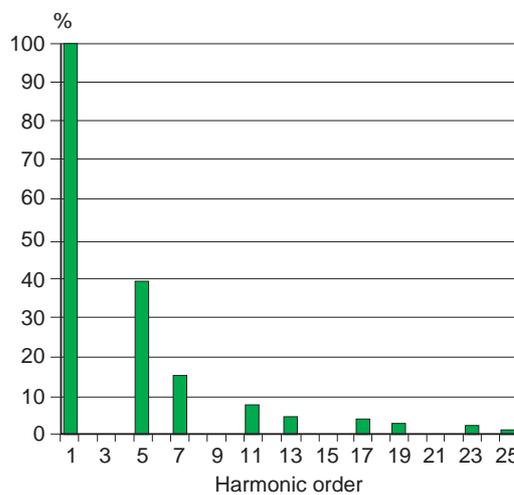


Fig. 7 : spectrum of the current drawn from the line supply (3-phase supply).

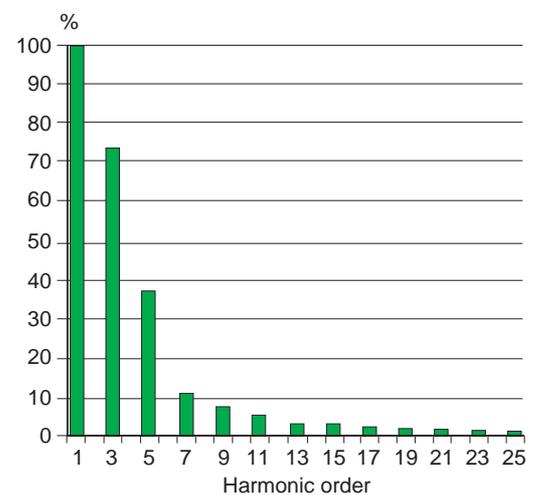


Fig. 9 : spectrum of the current drawn from the line supply (single-phase supply).

■ Variation of the line current according to the motor operating point
Since the fundamental current drawn by the drive is practically in phase with the voltage, the current is proportional to the electric power drawn from the line supply. If we disregard the efficiency, this current is therefore proportional to the mechanical power supplied by the motor. The mechanical power is equal to the product of the torque times the speed. Thus, at reduced speed the mechanical power is low. As a result, the current drawn from the line supply by the drive is low when the motor operates at low speed, even if the motor produces a high torque and takes a high current.

Standard references

Two standards are particularly concerned with the design of variable speed drives:

- IEC 61800-3 “Adjustable speed electrical power drive systems - Part 3: EMC product standard.”
- EN 50178 “Electronic equipment for use in power installations”. Conformity to this standard authorizes CE marking under the European “Low Voltage” directive.
It should be noted that this standard also gives details for installing these products.

1.2 Need for appropriate protection devices

The characteristics described above, both technological (electronic power circuits) and those relating to the operation of the motor combined with a drive, demonstrate the need for appropriate protection devices in order to make the best use of such equipment.
The creation of drives which incorporate electronic technology enables a number of these

protection devices to be integrated at a very reasonable cost.
Of course, these protection devices do not replace those that are required under existing regulations to be installed at the start of each circuit and which are thus “external” to the drives. Operation of all the protection devices used is described in the following sections.

2 Devices providing protection against overcurrents

The protection devices commonly used against overcurrents (circuit-breakers or fuses) are mainly provided to deal with two situations:

- To protect an installation against any risk of short-circuit.
- To avoid the risks resulting from a circuit overload or an operating current that exceeds

the capacities of the conductors (busbars and cables) and the control and protection equipment. Variable speed drive technology enables some of these functions to be provided electronically.

2.1 Protection devices integrated in drives

Motor overload protection

Modern variable speed drives protect the motor against overloads:

- by instantaneous limiting of the rms current to around 1.5 times the nominal current,
- by continuously calculating the I^2t , taking account of the speed (as most motors are self-ventilated, cooling is less efficient at low speed).

It should be noted that when a start circuit only supplies one motor and its drive, this motor overload protection simultaneously protects all the switchgear and wiring against overloads.

Protection against motor or line short-circuits downstream of the drive

If there is a short-circuit between phases at the drive output (at the motor terminals or anywhere on the line between the drive and the motor), the overcurrent is detected in the drive and a blocking order is sent very quickly to the IGBTs. The short-circuit current (see **fig. 10**) is broken within a few microseconds, which protects the drive. This very fleeting current is mainly provided by the filter capacitor used with the rectifier, and is therefore imperceptible in the power supply line.

Other protection devices integrated in drives

Drives have other self-protection functions against:

- Overheating of their electronic components that could result in their destruction. A sensor placed on the heatsink stops the drive when the temperature exceeds a certain threshold.
- Line voltage dips: This protection is necessary to avoid any malfunction of the control circuits

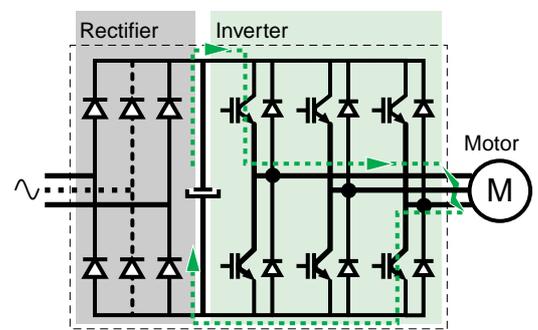


Fig. 10 : short-circuit downstream of the drive.

and the motor, as well as any dangerous overcurrent when the line voltage returns to its normal value.

- Overvoltages at the line supply power frequency: This avoids possible destruction of their components.
- Loss of a phase (for 3-phase drives): because the single-phase supply which replaces the 3-phase supply triggers an increase of the current drawn.

Operation of the integrated protection devices

If there is a fault, all these devices lock the drive and bring the motor to a “freewheel” stop. The power supply is then cut by the line contactor (its opening is controlled by a relay integrated in the drive).

2.2 Protection devices external to drives

In addition to the requirements described at the beginning of this section, these devices for protection against overcurrents are also designed to operate if there is an internal fault in the drive (destruction of the rectifier bridge for example): the line protection device breaks the fault current.

Note: Although this device cannot normally protect the drive components, its automatic opening limits the consequences of such faults.

Location of the devices

The most common circuit layout for which these protection devices have been defined appears in **figure 11** :

- with, at the start of the circuit, individual protection against overcurrents often associated with a contactor,
- without a breaker device downstream of the drive. The functions of the various devices (circuit-breaker, contactor and drive) are shown on this diagram.

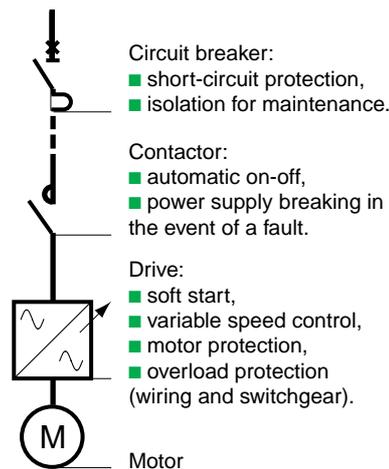


Fig. 11 : recommended diagram for overcurrent protection.

These combinations (circuit-breaker, contactor and drive) offered by manufacturers are called “motor combinations”. Due to the protection devices integrated in the drives, these combinations naturally provide type 2 coordination if there is a short-circuit downstream of the drive.

“Type 2 coordination” means that if there is a short-circuit:

- no damage or loss of adjustment is permitted,
- the insulation must be maintained,
- the motor combination must be able to operate after the short-circuit has been removed,
- the risk of contact welding on the contactor is permitted if these contacts can be separated easily.

If there is a short-circuit risk upstream of the drive, in order to provide type 2 coordination, it is necessary to refer to the coordination tables provided by the manufacturers of the protection devices placed upstream.

Note: With a drive, there is no current peak on power-up, and therefore no particular stress placed on the protection device.

Calculation of the circuit-breaker and contactor rating

This is determined according to the line current drawn by the drive. It is calculated based on:

- the motor nominal mechanical power,
- the nominal supply voltage,
- the efficiency of the motor and the drive,
- a permissible continuous overload of 1.1 T_n at constant torque and 1.05 T_n at variable torque,
- harmonics, since the current is not sinusoidal. The rms value of the current, depending on the harmonic distortion, is obtained using the formula:

$$I_{rms} = I_1 \sqrt{1 + THD^2}$$

thus, when THD = 40 %, $I_{rms} = 1.08 I_1$.

Since the fundamental current I_1 is practically in phase with the voltage, the typical value of the current drawn by the drive, when it supplies a motor operating at its nominal point (constant torque application), is calculated using the formula:

$$I_{rms} = 1.08 I_1 \approx 1.08 \times 1.1 \frac{P_{mot}}{\sqrt{3}U} \frac{1}{\eta_{mot}} \frac{1}{\eta_{drive}}$$

Where:

- P_{mot}: motor nominal power
- U: phase-to-phase voltage
- η_{mot}: motor efficiency
- η_{drive}: drive efficiency

- Example:
- Motor rating: 15 kW
- Line voltage: 400 V
- η_{mot} : 0.95
- η_{drive} : 0.97
- giving: $I_{rms} = 27.9$ A

Two special cases

■ Motors supplied in parallel
 In this case the overload protection integrated in the drive cannot protect each motor. This means that one of the motors could have an overload, although the current drawn by all the motors together does not exceed the drive nominal current.

The motors must therefore be protected individually by a thermal overload relay (see **fig. 12**).

It is however recommended that the overload protection integrated in the drive should remain active, in order to protect the cables upstream.

■ Integral drive overload protection disabled
 For certain applications for which continuity of operation is essential, the drive overload protection can be disabled. The cables and switchgear, which must be protected upstream, must therefore have an overload protection associated with the motor combination circuit-breaker (see **fig. 13**).

Oversizing of the cable and the switchgear by 20% is recommended in this situation.

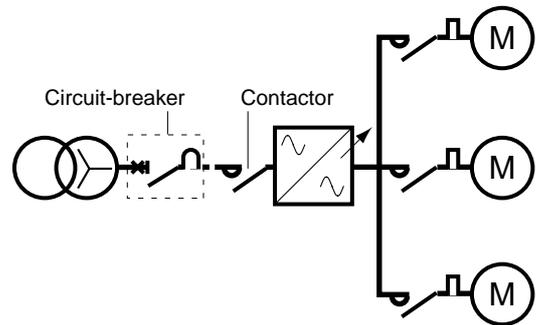


Fig. 12 : overload protection of a number of motors supplied by the same drive.

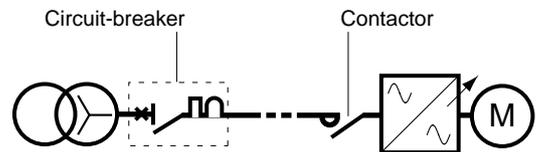


Fig. 13 : integral drive overload protection disabled.

3 Protection of persons

3.1 Risks connected with insulation faults

An insulation fault, whatever its cause, presents risks for:

- the safety of persons (risk of electric shock),
- the safety of property (risk of fire or explosion due to excessive localized temperature rise),
- the availability of the electrical power (disconnection of part of an installation in order to eliminate the fault).

The standards and regulations concerning the protection of persons identify two types of dangerous contact and stipulate the corresponding protection measures.

Direct contact

Persons coming into contact with live conductors (phase or neutral) or conductive parts that are normally live (see [fig. 14](#)).

Protection against this risk is usually provided by insulating the live parts using barriers, screens or enclosures (in accordance with IEC 60364-4-41). These devices are of a preventive nature and are not fool proof. To alleviate any risk, an additional, automatic break protection measure is used, consisting of the detection of any earth leakage current which may circulate through a person, and which does not loop back to the source via the live conductors. Its trip threshold is set at **30 mA for AC current** (IEC 60364-4-41) and 60 mA for DC current.

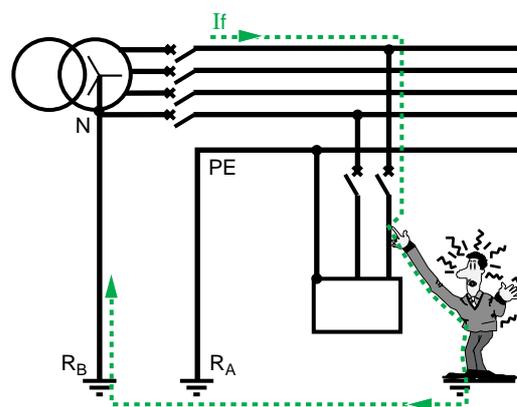
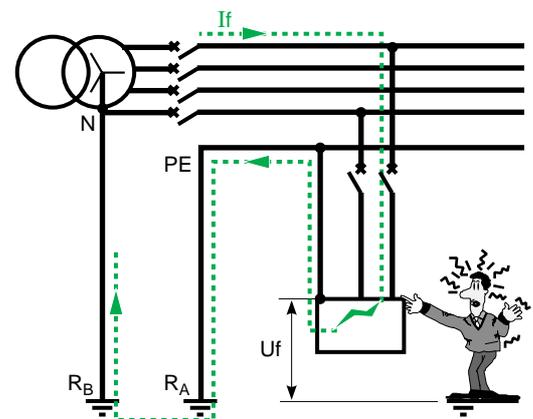


Fig. 14 : direct contact.

Indirect contact

Persons coming into contact with conductive metal frames, which are normally volt-free, and accidentally become live. This energizing is the result of failure of the insulation of a device or a conductor leading to an insulation fault (see [fig. 15](#)).

This electrical risk depends on the contact voltage that develops between the frame of the faulty equipment and the earth or other conductive metal frames located nearby. Depending on the electrical connections between the live conductors, frames and earth, the standards provide different installation diagrams for defining the protection devices to be used. For further explanations see "Cahier Technique" no. 172.



In the event of contact with a frame which is accidentally energized (U_f) the danger threshold is fixed by the safety limit voltage U_L .

Thus where:

R_A = earthing resistance of the installation frames,

R_B = earthing resistance of the neutral,

the operating threshold ($I\Delta n$) of the protection device must be such that:

$$U_f = R_A \cdot I\Delta n \leq U_L$$

$$\text{and then } I\Delta n \leq U_L / R_A.$$

(For more details, please refer to Cahier Technique no. 114)

Fig. 15 : indirect contact.

3.2 Summary of earthing systems

There are three types of earthing system, commonly known as neutral point connection, for LV networks. They differ according to whether or not the neutral point of the voltage source is earthed and also the method used to connect the frames (see **fig. 16**). The choice of the neutral point connection depends on the installation characteristics and the operating conditions and requirements.

For further details see also the following "Cahiers Techniques":

- No. 173 - Earthing systems worldwide and evolutions,
- No. 178 - The IT earthing system (unearthed neutral) in LV.

TT system

In this type of system, known as "directly earthed neutral":

- the source neutral is connected to a separate earth connection from that of the frames,
- all frames protected by one breaking device must be connected to the same earth connection.

This is typically the case with public distribution in France.

The TT system requires immediate breaking since any insulation fault may present a risk of electrocution.

TN system

The principle of this system, known as "neutral connection", is that any insulation fault will trigger a single-phase short-circuit between phase and neutral. Immediate breaking is also essential and this system allows the use of the usual overcurrent protection devices to protect against insulation faults. In this type of system:

- the LV neutral point of each source is connected directly to earth,
- all frames in the installation are earthed (and thus connected to neutral) via a protective earth conductor :
- PE separate from the neutral conductor; this is the TN-S system,
- or common PEN with the neutral conductor; this is the TN-C system.

Note: The TN-C system is not recommended for supplying electronic devices due to the possible circulation of harmonic currents in the neutral conductor that is also the protective earth.

IT system

In this type of system known as "unearthed neutral":

- The transformer neutral is:
- either isolated from the earth (unearthed neutral),
- or earthed via a high impedance (impedance-earthed neutral),

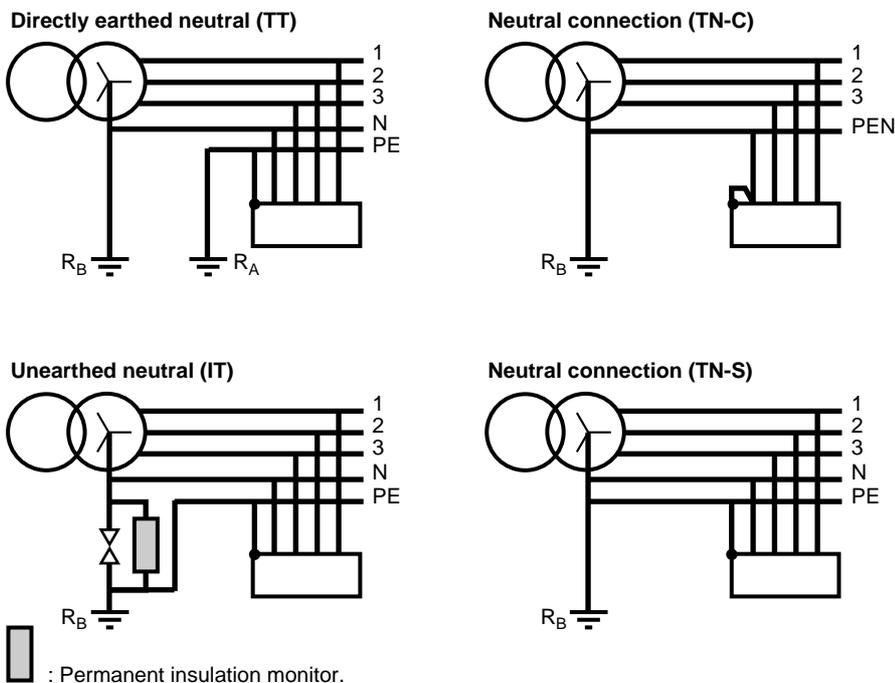


Fig. 16 : the three standard types of earthing system.

■ all frames in the installation are connected to one another and earthed.
 In the IT system, the first insulation fault does not require breaking to take place, which enables the installation to continue to operate normally. However, this fault must be detected, signaled and then repaired before a second insulation fault occurs on another live conductor, which would then require an immediate trip. This rule gives the IT system the best continuity of service (see also "Cahier Technique" no. 178).

Need for special detection methods

The value of the insulation fault current between phase and earth (in common mode) depends on the earthing system. Its value is often too low to be detected and eliminated by conventional overcurrent protection devices (thermal or magnetic protection of a circuit-breaker), as is the case with the TT and IT systems.

Two devices are designed particularly for protecting persons: Residual Current Devices - RCDs - and Permanent Insulation Monitors - PIMs -.

■ Residual Current Devices

□ Principle of RCDs

This is illustrated in **figure 17**.

If there is no insulation fault, the algebraic sum of the currents in the live conductors is zero and the toroid is not subjected to any magnetomotive force.

If there is an insulation fault, this sum is no longer zero and the fault current creates a magnetomotive force in the toroid that generates a current in its coil. If the current exceeds a fixed threshold for a period longer than the optional time delay, an opening command is transmitted to the breaking device.

For further details, see "Cahier Technique" no. 114: "Residual current devices in LV".

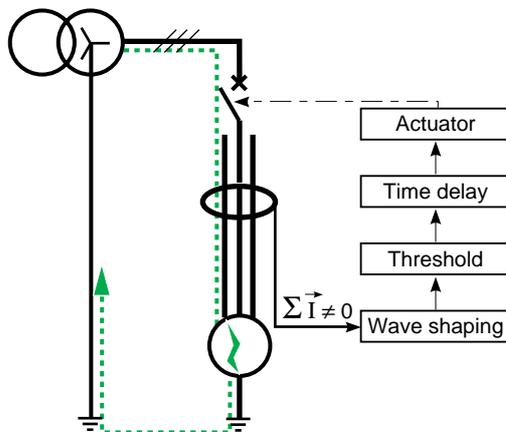


Fig. 17 : principle of the RCD.

□ Types of RCD

Standard IEC 60755 distinguishes three types of residual current protection device:

AC: For sinusoidal AC currents

A: For AC currents with a DC component (see **fig. 18**). These devices are suitable for detection of rectified single-phase currents.

B: For DC currents. These devices are suitable for all types of current and are necessary, in particular, for rectified 3-phase currents.

■ PIMs

The principle of a PIM consists of injecting an AC or DC voltage between the line supply and the earth (see **fig. 19**). The measurement of the current crossing the monitor is used to calculate the insulation resistance when this is a DC current, and that of the line supply/earth impedance when this is an AC current.

These measurements associated with threshold devices authorize different alarms, for example that for the gradual reduction of insulation for the purpose of planned maintenance, or for an earth fault requiring rapid intervention (before the second fault).

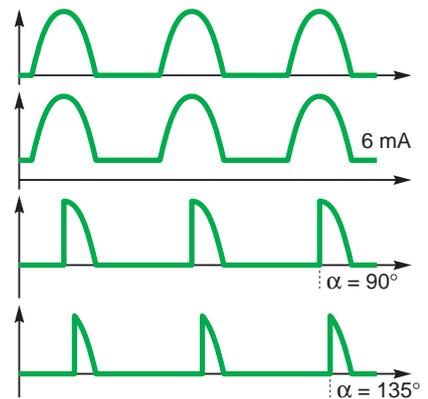


Fig. 18 : waveforms which characterize type A RCDs.

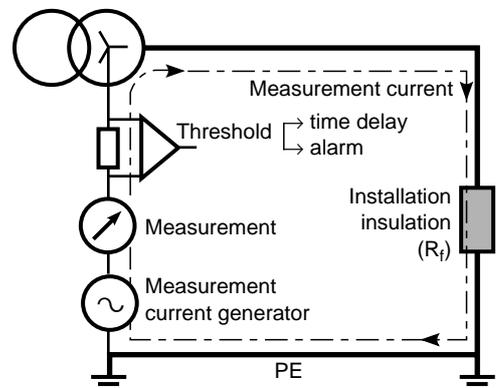


Fig. 19 : principle of a PIM.

3.3 Use of RCDs according to the earthing system

“Cahier Technique” no. 172: “Earthing systems in LV” covers this subject in greater depth.

For all earthing systems

RCDs are used as additional protection against the risks of direct contact. In certain countries they are even compulsory upstream of ≤ 32 A power sockets with a ≤ 30 mA trip threshold (for example, in France, according to standard NF C 15-100 §532.26).

RCDs with a sensitivity less than or equal to 500 mA (IEC 60364, section 482) are also recommended for monitoring electrical supply circuits in areas where there is a risk of fire.

TT system

The use of RCDs is the only method of detecting low fault currents. In fact, the impedance of a fault is not known with certainty and may be high (the load frames have separate earth connections and are not always connected to one another).

TN-S or TN-CS system

Using RCDs avoids the need to check the value of the current if there is a fault.

They also control breaking of the circuits when the fault current, limited by a very long cable, is insufficient to activate the overcurrent protection devices. The trip threshold of the RCDs may then be high (low sensitivity), from a few amps to tens of amps.

Note: According to IEC 60364:

- a residual current device should not be used in a TN-C system,
- when a residual current device is used in a TN-C-S system, a PEN conductor should not be used downstream.

IT system

In an IT system, RCDs are used in the following two situations.

- If the short-circuit current (at the 2nd fault) may not be sufficient to activate protection against faults between phases, for example on feeders supplying loads which are a long distance away.
- For groups of receivers connected to earth individually (groups of frames not connected to one another).

3.4 Earth fault protection devices integrated in drives

If the line supply has a TN system, a fault between a drive output and earth causes a significant overcurrent due to the interconnection of the frames (see [fig. 20](#)). As with a short-circuit between phases, this overcurrent is detected and a blocking command is sent to the IGBTs. However, in this situation

the fault current circulates in the power supply line for a very short time (a few hundred microseconds). The integrated protection device then intervenes. The drive is electrically isolated by the opening of the line contactor. This device does not protect persons against indirect contact under all

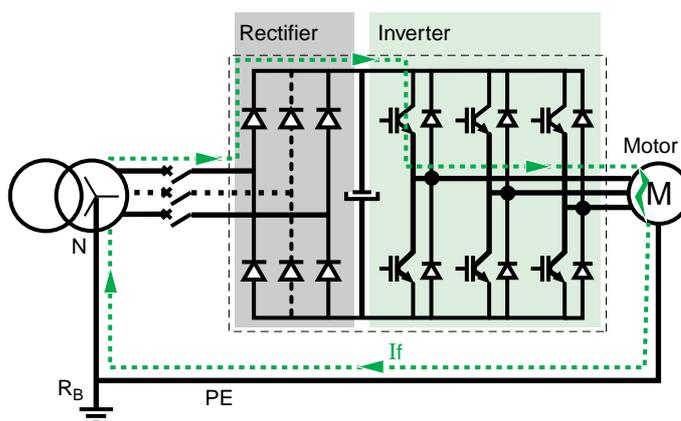


Fig. 20 : earth fault at the output.

circumstances. In fact, the impedance of the fault may limit the current to a value that is below the drive's protection threshold. This is generally the case with the TT system. A 300 mA RCD is therefore necessary.

In the case of an IT system, the first fault does not cause current to circulate and the drive continues to operate normally.

3.5 Insulation faults and variable speed drives

Direct contact

There are a number of possible direct contact situations on circuits containing variable speed drives (see **fig. 21** hereafter and **fig. 22** next page).

■ TT and TN-S systems

An additional protection device, in the event of failure of other protection measures against contact or carelessness by users, can be provided upstream of the drive using an RCD with a 30 mA threshold.

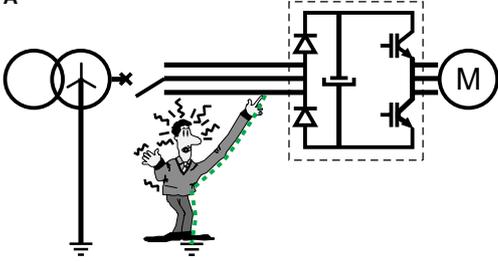
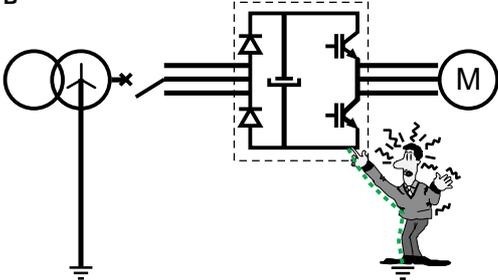
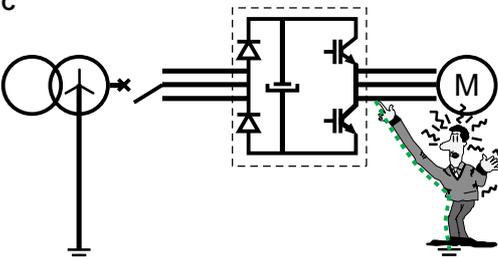
Risk of direct contact	Contact voltage	Additional protection
<p>Upstream of the drive A</p> 	Phase - neutral voltage	30 mA RCD
<p>On the DC bus B</p> 	Rectified line voltage	
<p>Downstream of the drive C</p> 	Drive output voltage	

Fig. 21 : voltages present in the event of direct contact with TT and TN-S systems.

■ IT system with a first insulation fault present on the line supply

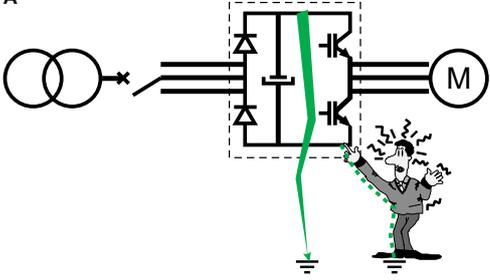
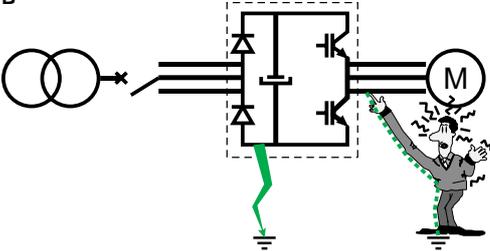
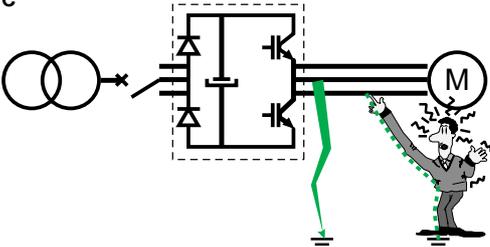
Risk of direct contact	Contact voltage	Additional protection
<p>A</p> 	Rectified line voltage	No automatic break protection possible
<p>B</p> 	Drive output voltage	
<p>C</p> 		

Fig. 22 : various situations specific to a line supply with an IT system which has an insulation fault and a person in direct contact.

In the three situations specific to the IT system shown in figure 22, no automatic break protection can be applied: the fault current cannot be distinguished from the normal

operating current. This underlines the importance that installers must give to the wiring of these machines in order to ensure the basic precaution, i.e. insulation of live parts.

Notes:

- The same is found for each of these situations when the two faults (insulation and direct contact) are swapped.
- When a number of drives are powered via the same line supply, the DC buses of the different drives can be considered as being at the same voltage. Faults on different drives therefore have the same consequences as if they were located on one drive.

Indirect contact

■ TT and TN-S systems

The indirect contact situations are shown in **figure 23**.

■ IT system

With this system the presence of two simultaneous faults must be taken into account. The table in **figure 24** gives the various possible faults and their consequences.

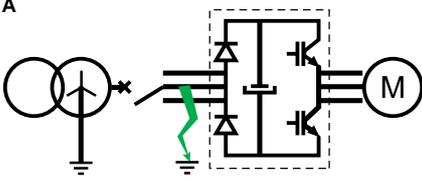
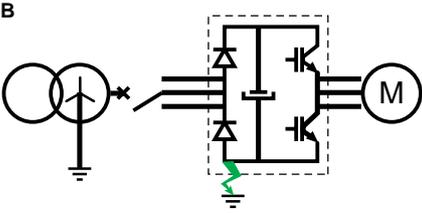
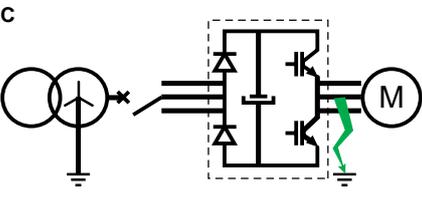
Situation	Effect... (risk...)	Relevant protection with a TT system	Relevant protection with a TN-S system
A 	Overcurrent upstream of the drive	RCD	Overcurrent protection placed upstream
B 	Overcurrent across a diode of the rectifier bridge. The fault current is a rectified current. (Risk of irreparable damage)	RCD immune to passage of DC current	
C 	Overcurrent across a diode of the rectifier bridge and an IGBT. (Risk of irreparable damage depending on the type of "short-circuit" protection integrated in the drive)	Internal in the drive or RCD	Internal in the drive or overcurrent protection placed upstream, but a very long cable downstream of the drive may mask the fault, and an RCD is therefore recommended

Fig. 23 : various insulation faults with TT and TN-S systems.

Situation	Effect... (risk...)	Relevant protection
A 	Overcurrent upstream of the drive	Overcurrent protection placed upstream
B 	Overcurrent across a diode of the rectifier bridge (Risk of irreparable damage)	Overcurrent protection placed upstream
C 	Overcurrent across a diode of the rectifier bridge and an IGBT (Risk of irreparable damage depending on the type of "short-circuit" protection integrated in the drive)	Internal in the drive or overcurrent protection placed upstream, but a very long cable downstream of the drive may mask the fault.
D 	Short-circuit on the DC bus (Risk of irreparable damage to the rectifier bridge)	Overcurrent protection placed upstream
E 	Short-circuit at the terminals of an IGBT (Risk of irreparable damage to the opposite IGBT depending on the type of "short-circuit" protection integrated in the drive)	Internal in the drive or overcurrent protection placed upstream
F 	Overcurrent at the drive output	Internal in the drive

Fig. 24 : various situations with two dead shorts or low impedance faults on an IT system.

■ Special case of motors supplied via two separate circuits each containing a drive, where the frames have separate earth connections. When an installation supplies a number of devices that are a long way away from one another, the load frames are often connected with separate earth connections. The impedance of the circuit through which the fault current runs is thus increased by the resistance of the two earth connections concerned. The condition required for the protection of persons (compliance with maximum breaking times) can no longer be met by the short-circuit protection devices.

The usual solution, which is very simple both to design and install, is to use RCDs (see "Cahier Technique" no. 178) placed at the start of each

circuit containing a separate earth connection (see **fig. 25**). These RCDs must not be disturbed by the passage of a DC component.

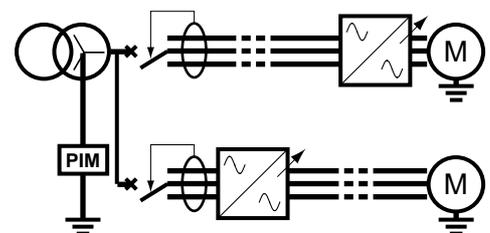


Fig. 25 : positioning of RCDs in an IT system to protect two circuits with separate earth connections.

4 Protection devices to be used with drives (summary table)

The following table summarizes the preceding sections, listing the protection functions provided by the drive, and if necessary the addition of devices external to the drive such as circuit-breakers, thermal overload relays, and RCDs.

Protection to be provided	Protection generally provided by the drive	External protection
Cable overload	Yes = (1)	Unnecessary if (1)
Motor overload	Yes = (2)	Unnecessary if (2)
Downstream short-circuit	Yes	
Drive overheating	Yes	
Overvoltage	Yes	
Undervoltage	Yes	
Phase break	Yes	
Upstream short-circuit		Circuit-breaker (short-circuit trip)
Internal fault		Circuit-breaker (short-circuit and overload trip)
Downstream earth fault (indirect contact)	Self-protection	RCD \geq 300 mA
Direct contact fault		RCD \leq 30 mA

5 Special phenomena

The purpose of this section is to analyze the special phenomena connected with the operation

of frequency converters, which affect RCD and PIM protection devices.

5.1 High-frequency leakage currents

The voltage waveform generated by the drive, and in particular the presence of transient voltage fronts generated by switching of the IGBTs, causes high-frequency leakage currents to circulate in the power supply cables.

Flows

These voltage fronts are applied to the different capacitances in the circuit (see [fig. 26](#)):

C_c : capacitance of the IGBT components between conductors and enclosure connected to earth,
 C_m : capacitance between the motor windings and earth (depending on the motor rating),
 C_r : capacitance between the line supply and earth (short-circuited if the neutral is connected to earth),
 C_s : capacitance between the output conductors and earth (depending on the type and length of the cables),
 C_y : interference suppression capacitance at the drive input.

Currents therefore circulate across these capacitances. The most significant are shown in [figure 27](#).

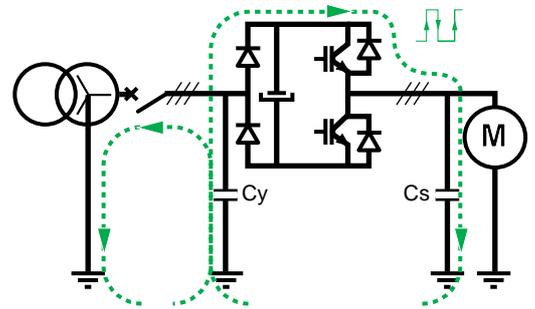


Fig. 27 : circulation of high-frequency leakage currents.

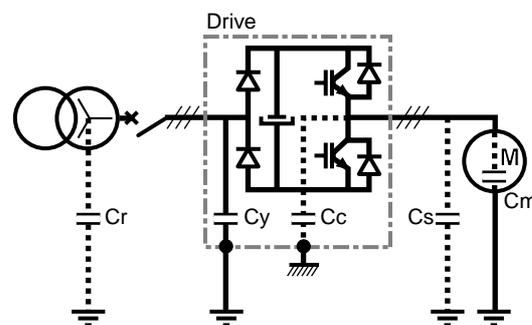


Fig. 26 : capacitances in the circuit.

Characteristics

These currents may reach an instantaneous value of several amps and an rms value of several dozen or several hundred milliamps. The spectrum and amplitude of these currents depend both on the PWM frequency (between 1 and 20 kHz) and the installation characteristics:

- power supply: line impedance, earthing system,
- type and length of the motor cable (shielded, not shielded, protective earth),
- motor rating,

The shape and spectrum of the HF currents at the drive input (when there is no fault), for a PWM at 4 kHz, are shown in [figures 28](#) and [29](#).

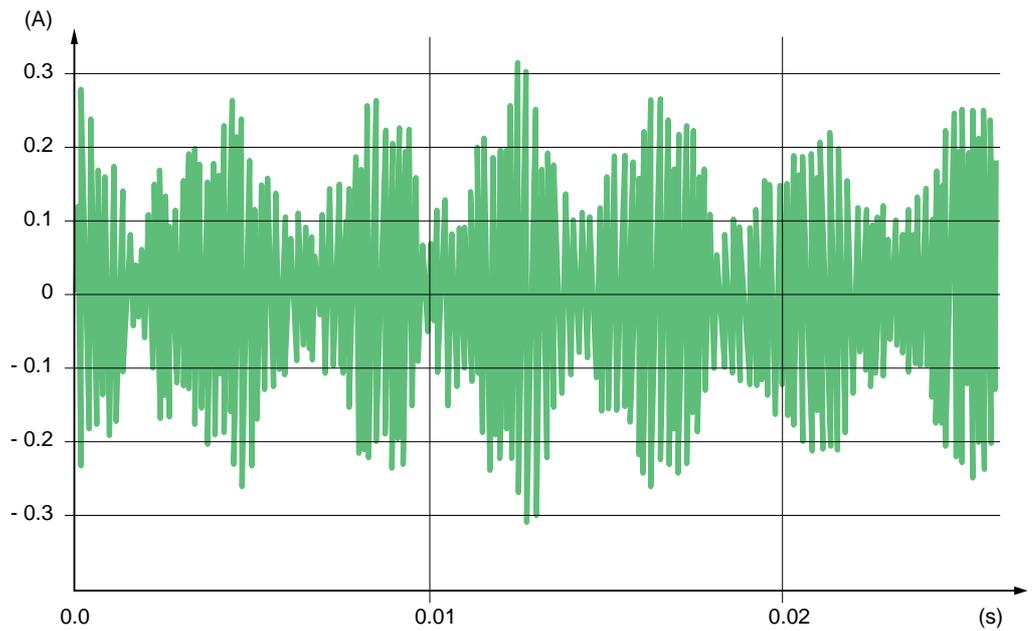


Fig. 28 : high-frequency leakage currents.

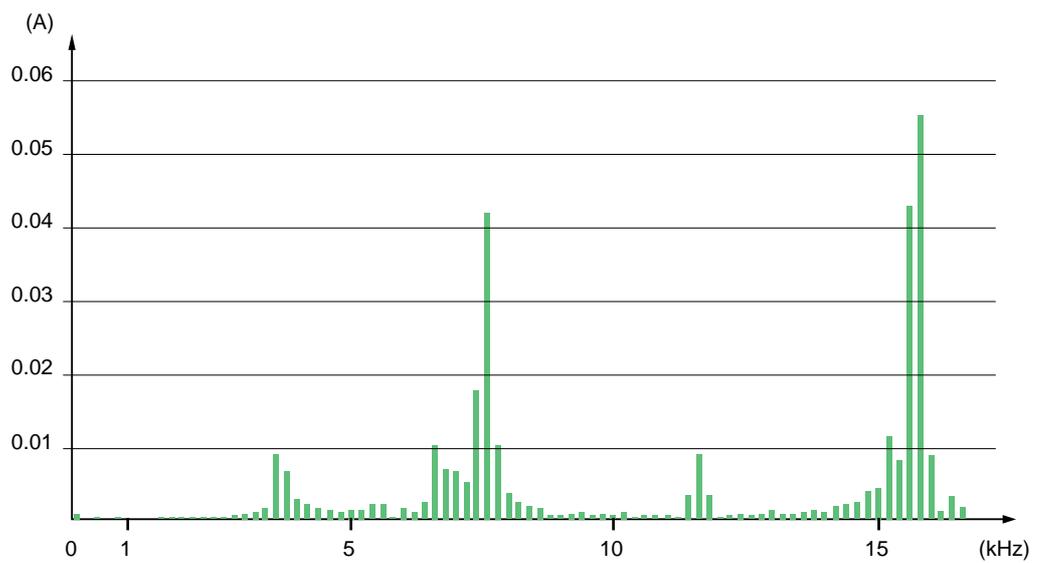


Fig. 29 : spectrum of the leakage current.

Their effect:
risk of disturbance of RCDs

■ Undesired tripping

These currents may cause malfunctioning of the residual current devices (RCD) when they flow through conductors surrounded by the measurement toroid. The measurement of the residual current may therefore be disturbed, in particular when the drive – motor connection cable is very long and/or the capacitances between phases and earth are high (see **fig. 30**).

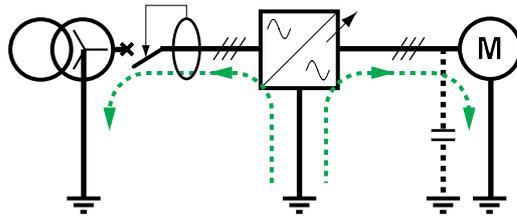


Fig. 30 : disturbance of an RCD by high-frequency leakage currents.

Solution

The measurement device must therefore include a filtering circuit so that only the low-frequency component of the signal is taken into account (see **fig. 31**).

Additional precautions, given at the end of this “Cahier Technique”, may be necessary in certain extreme situations.

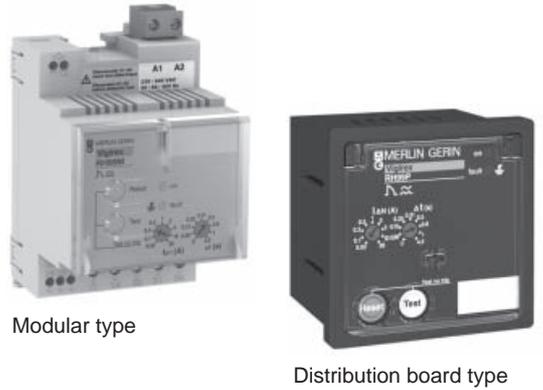


Fig. 31 : RCD integrating filtering of HF currents (Vigrex RH99M and RH99P – Merlin Gerin brand).

5.2 Leakage currents on power-up

Origin

Capacitors are generally placed at the input of frequency converters to provide them with immunity from the HF interference present on the line supply and reduce their HF emissions. Their capacitance is around 10 to 100 nF. These capacitors are responsible for residual currents (see **fig. 32**) at power-up and during normal operation.

Their effect: risk of undesired tripping

For a device that is operating normally, these currents are low (from 0.5 to 3.5 mA). However, in an industrial device that contains a number of drives, they can cause undesired tripping of RCDs.

Solution

This is the responsibility of the equipment manufacturer or the installer. It consists of limiting the number of drives supplied by the same RCD.

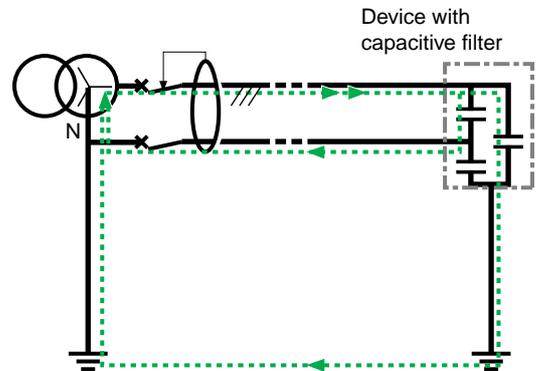


Fig. 32 : leakage current flowing through the input capacitors of devices (dotted lines).

5.3 Fault at the drive output with a TT or TN system

Risk of electrocution

The fault current contains a component at the PWM frequency and HF currents created by the oscillations of the stray capacitances, but the dangers of HF currents are not widely known. Document IEC 60479-2 provides information in particular on the variation of the threshold of cardiac fibrillation.

This curve (see **fig. 33**) shows that the frequency factor, which is the ratio of the current at frequency f to the current at 50/60 Hz frequency when considering the same physiological effect, increases with the frequency. It therefore permits a higher trip threshold for current frequencies higher than 50 Hz. This threshold variation is achieved technically by filtering.

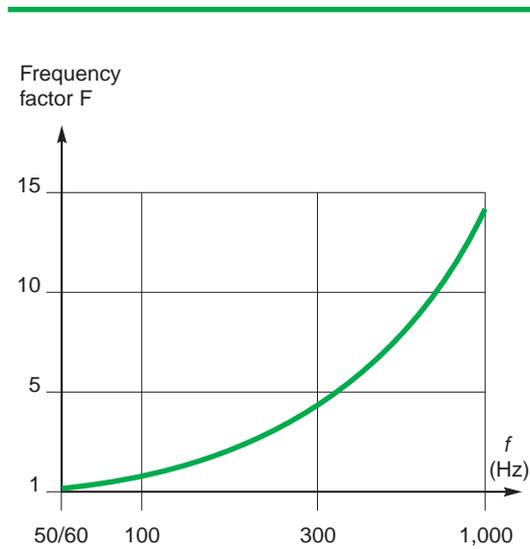


Fig. 33 : variation of the cardiac fibrillation threshold as a function of the frequency (according to IEC 60479-2).

Shape of the fault current

If there is a dead short to earth at the drive output, with a TN system, the overcurrent trips the internal drive protection or the overcurrent protection devices placed upstream.

If the impedance of this insulation fault is high, the overcurrent protection threshold may not be reached, and an RCD must therefore be fitted to provide this protection.

As already explained, correct operation of an RCD depends on the fault currents passing through its toroidal sensor, thus in this example these currents are not perfectly sinusoidal. The waveform of the zero-sequence fault current can be analyzed by examining the simplified equivalent circuit diagram in **figure 34**.

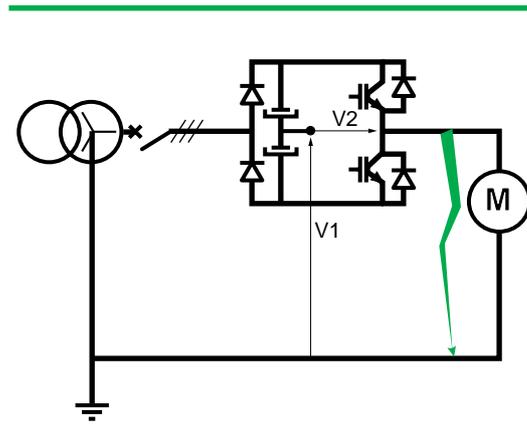


Fig. 34 : fault voltage.

Voltages $V1$ and $V2$ are responsible for circulating any fault current that may occur, as shown in **figure 35**.

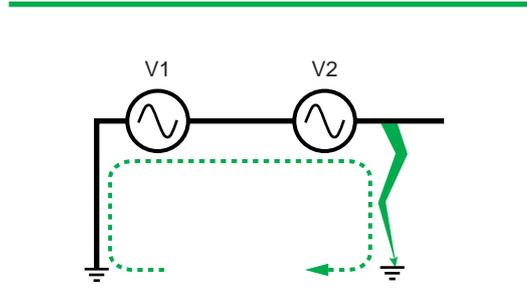


Fig. 35 : fault current.

The fundamental frequency of voltage V1, between the neutral of the 3-phase supply and the central point of the rectifier, is 150 Hz (see [fig. 36](#)).

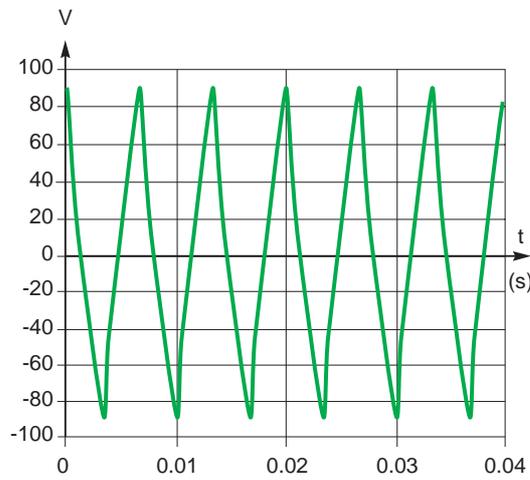


Fig. 36 : voltage of the rectifier neutral point with a 3-phase supply.

Voltage V2 (see [fig. 37](#)), between the central point of the rectifier and one output phase is the result of PWM. It therefore contains a low-frequency component equal to the drive output frequency (40 Hz in this example) and a component at the PWM frequency (1 kHz in this example).

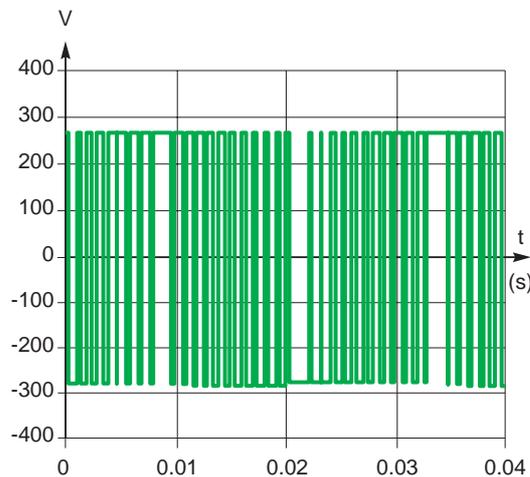


Fig. 37 : output voltage of the inverter stage.

This results in a fault current containing all of the following components:

- 150 Hz,
- drive output frequency,
- modulation frequency,
- and their harmonics.

Its shape is shown in [figure 38](#). This fault current also contains the HF currents described in the preceding sections, but not included here in order to simplify the illustrations.

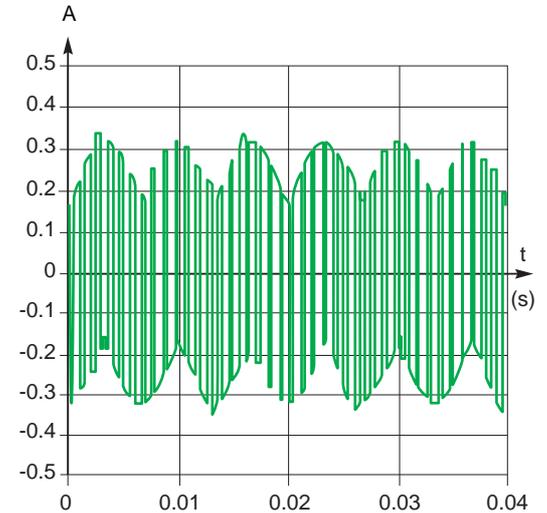


Fig. 38 : fault current with a 3-phase supply.

As shown in [figure 39](#), the amplitude of the various components changes as a function of the motor operating frequency:

- The total rms value of the current remains constant, as does the 150 Hz component.
- Components at the motor supply frequency and the PWM frequency vary in opposite ways.

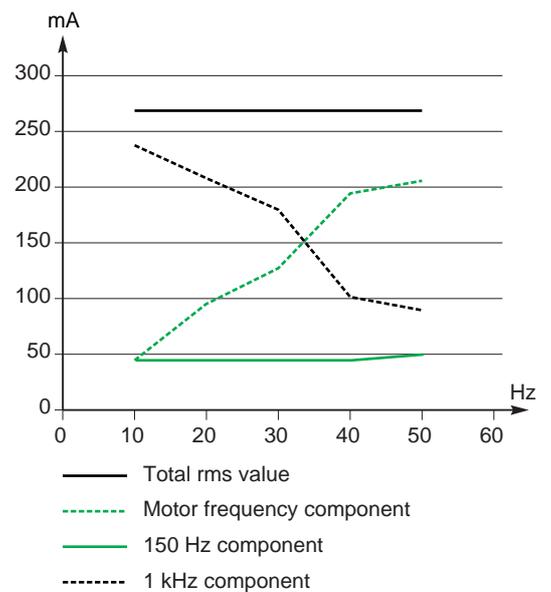


Fig. 39 : evolution of the fault current components.

The shape of the fault current for a single-phase power supply is shown in **figure 40** . Note that there is a 50 Hz component and not a 150 Hz component as with a 3-phase supply.

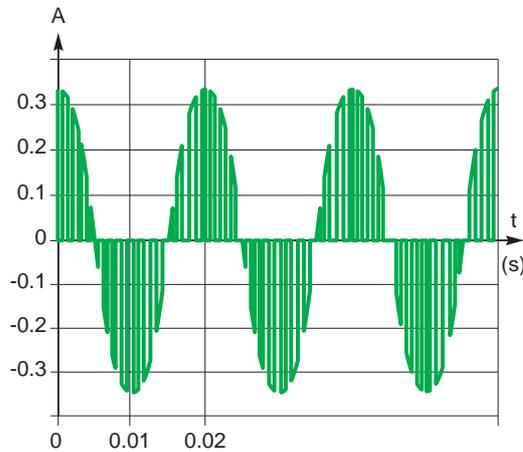


Fig. 40 : fault current with single-phase power supply.

Solution

The complex shape of the fault current requires the use of a type A RCD (see **fig. 41**).



Fig. 41 : example of a type A RCD suitable for use with an LV circuit-breaker (C60-300 mA Vigi unit – Merlin Gerin).

5.4 Fault at the drive output with an IT system

Rapid fluctuation of the line voltage with respect to earth

In an IT system, an earth fault at the drive output does not necessitate tripping, but will cause a rapid fluctuation in the line voltage relative to earth.

Unlike the TN system, the line voltage relative to earth is not actually fixed, and will follow the fluctuations set by the PWM. This is shown in the diagram in **figure 42** .

Any load connected to the line supply is therefore subject to the same fluctuations, including significant voltage gradients (see **fig. 43**). These gradients may result in damage to the capacitive filters connected between the line supply and earth.

Solutions

The use of EMC filters to improve Electromagnetic Compatibility is not recommended on supplies with IT systems (see standard IEC 61800-3).

When it is essential that HF emissions are reduced, a suitable solution is to place an EMC filter with no earth connection at the drive input.

To eliminate the phenomenon of rapid voltage fluctuation, it is advisable to install a “sinus” filter at the drive output. This eliminates any high voltage gradient applied to the motor and the power supply cable.

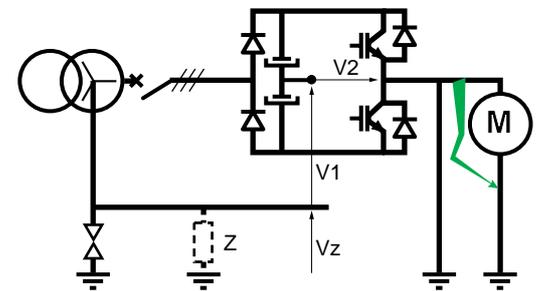


Fig. 42 : earth fault in IT system.

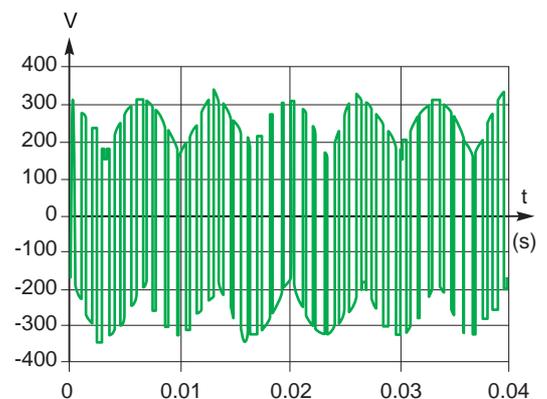


Fig. 43 : fluctuation of the line supply voltage.

5.5 Fault current with DC component

Description

Conventional protection devices are suitable for measuring AC fault currents. However, insulation faults on the DC bus of the drive or on the braking energy dissipation circuit (function performed by a resistor which is usually external to the drives) cause the circulation (see [fig. 44](#)) of a current with a DC component (see [fig. 45](#) with a 3-phase supply, and see [fig. 46](#) with a single-phase supply).

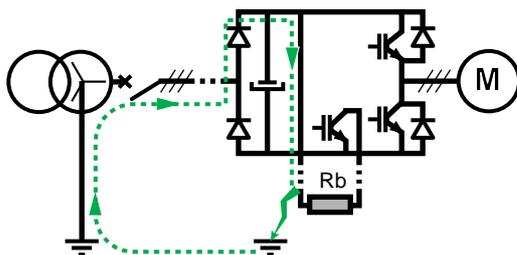


Fig. 44 : fault between the braking resistor and earth.

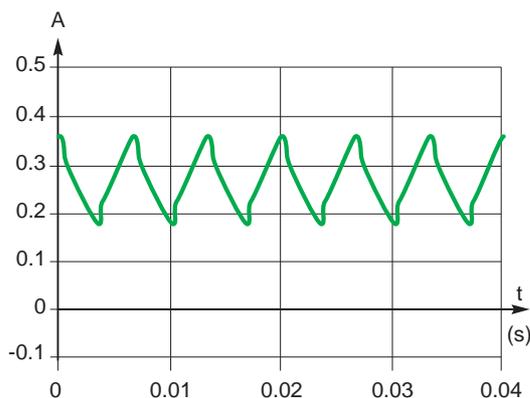


Fig. 45 : current in the event of a fault on the braking resistor, for a 3-phase supply and a fault resistance of 1 kΩ.

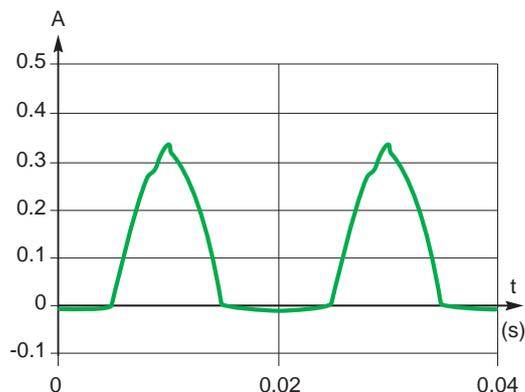


Fig. 46 : current in the event of a fault on the braking resistor, for a single-phase supply and a fault resistance of 1 kΩ.

Solution

The protection devices must remain operational despite this DC component.

If an insulation fault is possible on the DC bus, or on the braking resistor circuit, a type B RCD must be used when the drive has a 3-phase supply. When the drive has a single-phase supply, a type A RCD should be used.

Practical rule for using RCDs

- In the first situation, with an IT system, illustrated by [figure 47](#), the fault current has a DC component. The RCDs used to provide protection against direct contact must therefore be sensitive to this type of current.
- In the second situation (see [fig. 48](#)), two RCDs are connected in cascade.

If there is a fault on the DC bus, the fault current may not be sufficiently high to trip RCD2. Conversely, this current, which has a DC component, may be sufficiently high to saturate the measurement toroid of RCD1, preventing it from tripping if there is a fault on another feeder.

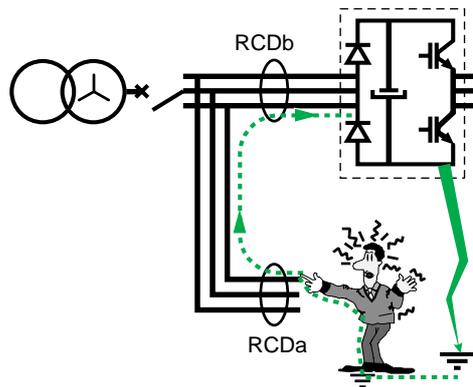


Fig. 47 : risk of "blinding" the RCDA.

■ The following rule is therefore used:
 If the fault current may have a DC component, a type A or B RCD is necessary, depending on the type of power supply. Thus all the RCDs in which this current may circulate should be identical type A or type B RCDs. This condition

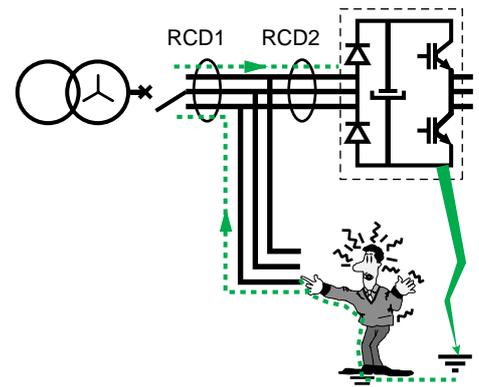


Fig. 48 : risk of "blinding" the RCD1.

is essential in particular in the following situations:

- when these RCDs are installed in series,
- in IT systems, since the RCDs may be affected by double faults occurring on different feeders.

6 Selection and installation recommendations

Based on the following principles:

- for the use of overcurrent protection devices (short-circuit and overload) covered in section 2,
- for the protection of persons, covered in section 3,
- then the special phenomena described in the previous section,

this section gives practical recommendations that answer the question: how can I provide correct protection for a circuit containing variable speed drives?

6.1 Selection of RCDs (see fig. 49)

	Protection...			
	... against indirect contact		... against direct contact	
Power supply	3-phase		Single-phase	
Hardware and installation characteristics	No double insulation of the DC bus	Double insulation of the DC bus	If an additional protection measure is necessary, in the event of failure of other measures providing protection against contact or carelessness of users (see installation standards)	
Earthing system TT (or IT with frames not connected together)	Type B, low sensitivity (≥ 300 mA)	Type A, low sensitivity (≥ 300 mA)	Type B 30 mA	Type A 30 mA
Earthing system TN-S	Type A, low sensitivity (≥ 300 mA) [*]			
Earthing system IT				

[*] The insulation fault is similar to a short-circuit. Tripping must normally be performed by the short-circuit protection device, but the use of an RCD is recommended if there is a risk of overcurrent protection devices not tripping.

Fig. 49 : type of RCD depending on the earthing system and the required protection.

Special recommendations:

- only connect one drive per RCD,
- provide an RCD as an additional protection

measure against direct contact when the braking resistor is accessible.

6.2 Selection of PIMs

DC injection PIMs can be "misled" by a fault causing a DC voltage between the line supply and earth. Depending on the polarity of this voltage, the insulation level will be falsely increased or decreased.

Only AC injection PIMs can therefore be used on supplies without any electrical isolation used to power devices containing DC buses, such as variable speed drives.

However, if there is a fault at a frequency converter output, the insulation measurement may be distorted (see fig. 50). The converter actually behaves like a voltage source with variable magnitude and frequency. This voltage is added to the measurement voltage injected by

the PIM. If the frequency of this voltage is close to the measurement frequency, the measurement is distorted.

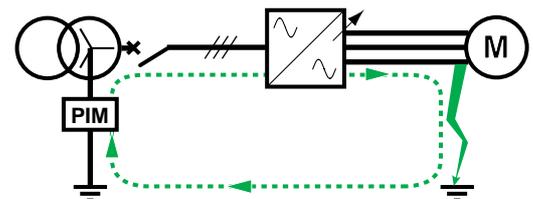


Fig. 50 : disturbance of measurement of the PIM.

6.3 Prevention of malfunctions

The disturbance described in the preceding sections may cause undesired tripping of the protection devices. For good continuity of service it is recommended that the following instructions are followed.

Precautions concerning RCDs

- Choose an appropriate model, which has:
 - filtering of HF currents,
 - a time delay (prevents any tripping due to the charging current of the stray capacitance on power-up). It is not possible to have a time delay for 30 mA devices. In this case, choose devices that are immune to undesired tripping, for example high-immunity RCDs in the **s.i.** range (Merlin Gerin brand).
- If possible raise the trip threshold, while keeping to the limit values set for the protection of persons.

These precautions are in addition to the rules described in section 5.5 on using RCDs.

Precautions concerning PIMs

Choose an appropriate model:

- AC injection type
- or
- coded pulse type, which makes the drive output frequency irrelevant.

Precautions concerning installation

Converters must be used in accordance with standards EN 50178 and IEC 61800-3.

Certain additional precautions may also be necessary.

- Reduce the capacitances to earth as much as possible. To do this:
 - avoid the use of shielded cables when the operating environment permits,
 - reduce the length of cable between the drive and the motor,
 - ensure that the wiring is carried out in line with accepted practice,
 - avoid the use of EMC filters or use filters with low capacitances (especially in IT systems).
- Reduce the PWM frequency (reduction of the number of switching operations per second and therefore reduction of the rms value of the HF currents).
- Divide the drives over a number of RCDs (to avoid bringing the leakage currents together).
- Place “sinus” filter at the drive output (elimination of voltage gradients applied to the cables).
- Use an isolation transformer and place the RCD upstream (separation of the circuit which is disturbed by the drive from its power supply).

Bibliography

“Products” standards

- IEC 60479: Guide to the effects of current passing through the human body.
- IEC 60755: General requirements for residual current operated protective devices.
- IEC 60947-2: Low voltage switchgear - Part 2: Circuit-breakers.
- IEC 61008: Residual current operated circuit-breakers for household and similar use.
- IEC 61009: Residual current operated circuit-breakers with integral overcurrent protection for household and similar use.
- IEC 61800-3: Adjustable speed electrical power drive systems - Part 3: EMC product standard.
- EN 50178: Electronic equipment used in power installations.
- UTE C 60-130: Dispositifs de protection à courant différentiel résiduel.
- NF C 61-420: Petits disjoncteurs différentiels.
- NF C 62-411: Matériel de branchement et analogues, disjoncteurs différentiels pour tableaux de contrôle des installations de première catégorie.

“Installation” standards

- IEC 60364: Electrical installations of buildings.

Schneider Electric Cahiers Techniques

- Residual current devices in LV.
R. CALVAS, Cahier Technique no. 114.
- Protection of people and uninterruptible power supplies.
J-N. FIORINA, Cahier Technique no. 129.
- Earthing systems in LV.
B. LACROIX and R. CALVAS,
Cahier Technique no. 172.
- Earthing systems worldwide and evolutions.
B. LACROIX and R. CALVAS,
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- Disturbances of electronic systems and earthing systems.
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