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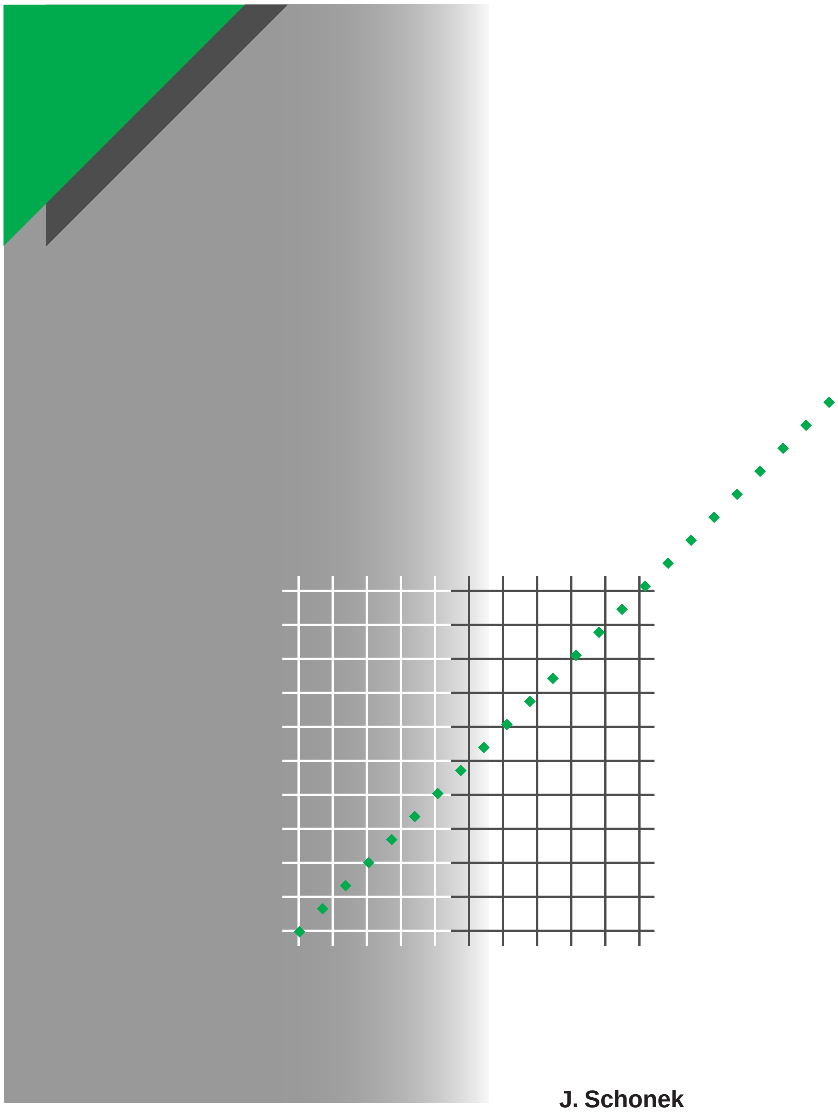
The neutral:
A live and unique conductor



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Foreword

no. 212

The neutral: A live and unique conductor

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Lexicon

i_r, i_s, i_t, i_N (A):	instantaneous values of currents in the phases and the neutral
I_N (A):	rms value of current in the neutral
I_L (A):	rms value of current in a phase
I_l (A):	Fundamental component of current I_L
i_h (%):	Harmonic ratio of order h of current I_L
I_h (A):	rms value of harmonic current of order h, $i_h\,(\%) = \frac{I_h\ (A)}{I_l\ (A)}\ 100$
THD (%):	Total Harmonic Distortion factor

The neutral:
A live and unique conductor

Paradoxically, although the neutral conductor is a live conductor, current should never be allowed to circulate in it.
Nevertheless, there has been renewed interest in the neutral conductor in relation to the proliferation of electronic loads, the circulation of harmonic currents and the risk of overloads.
Within this context, the aim of this document is to describe the current situation regarding typical and recommended installation rules with respect to breaking, protecting and dimensioning the neutral conductor.

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1 A live conductor in electrical distribution

2 Conventional rules for dimensioning and protecting the neutral

3 And now for harmonics…

1 A live conductor in electrical distribution

1.1 General system for electrical distribution

The most common system for low-voltage electrical distribution is the three-phase type system with distributed neutral. This arrangement enables both three-phase loads not connected to neutral (motors, for example) and single-phase common loads to be supplied with power at the same time.

The most common voltage levels used in Europe are 400 V phase-to-phase and 230 V phase-to-neutral (see **Fig. 1**).

The supply transformer secondary is therefore generally connected in a star or even a zigzag configuration.

Relevant regulations stipulate that when not also used as a protective earth conductor (PEN, in which case it should be green/yellow), the neutral conductor should be light blue in color.

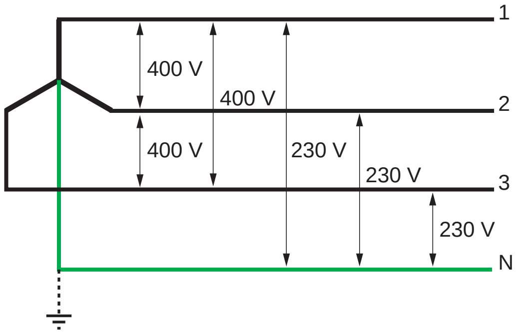


Fig. 1 : LV supply voltages

1.2 Neutral, but not passive

The neutral conductor has specific features in relation to other electrical distribution conductors.

- It has a specific role to play in the definition of earthing systems
  - It is generally possible and recommended to earth the neutral
  - It can be used as a protective earth conductor
- The neutral conductor is a **live conductor**
  - It provides single-phase loads with power
  - It supports the circulation of unbalanced currents
  - It supports the circulation of third harmonic currents from non-linear loads
  - Fault currents flow through it (insulation faults, overloads, short-circuits)

When it is used as a protective earth conductor, capacitive leakage currents flow through the neutral.

A certain number of **precautions** must be taken when designing an electrical installation:

- Specific regulations must be observed when dimensioning and protecting the neutral conductor.
- The continuity of the neutral conductor is imperative when it is used as a protective earth.
- The neutral conductor must be disconnected if its voltage in relation to earth increases to a dangerous level.

1.3 Summary of earthing systems

This summary is designed to provide a precise description of the specific role played by the neutral conductor in the definition of earthing systems.

An earthing system is selected with two objectives in mind:

- The protection of persons and property
- Service continuity

To counter the risk of electric shocks, installation standards have defined fundamental principles for the protection of persons. These are:

- The earthing of machine frames and electrical loads
- The equipotentiality of frames that can be accessed simultaneously, which tends to eliminate contact voltages
- Automatic disconnection of the electrical power supply in the event of dangerous voltages or currents caused by the circulation of the insulation fault current.

There are 3 types of earthing system 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. 2**). The choice of neutral point connection depends on installation characteristics as well as on operating conditions and requirements.

TT system

In this type of system (see Fig. 2a), 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 and other major countries.

Figure 3 illustrates the circuit with current flowing through it in the event of a fault.
The contact voltage on the frame of the faulty device is reaching a dangerous level.

The TT system therefore requires immediate breaking on the first insulation fault.
The breaking device fitted is a residual current device (RCD).

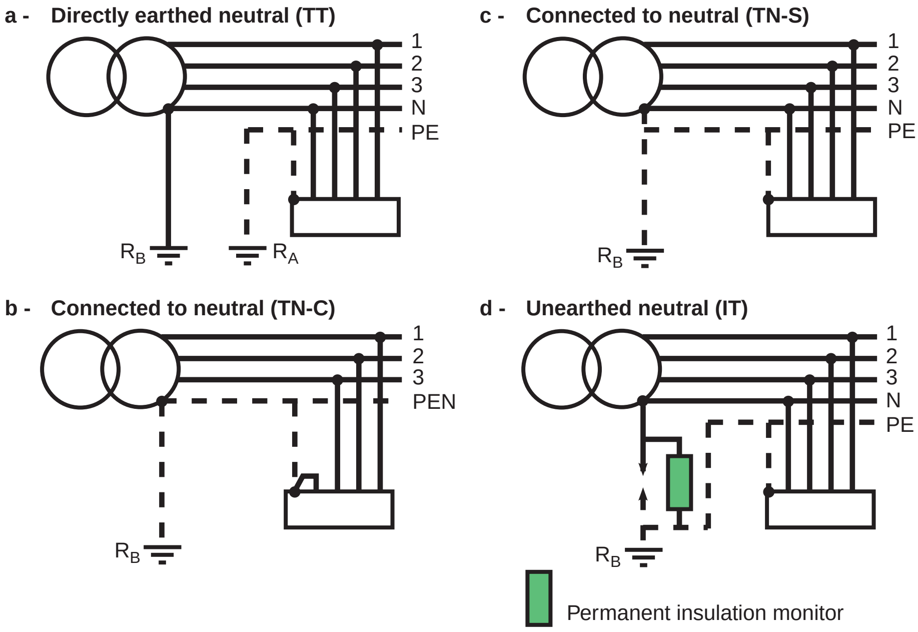


Fig. 2 : The three main types of earthing system are TT, TN and IT, as defined by IEC 60364-3. A TN system may be either TN-C (common neutral and PE) or TN-S (separate neutral and PE)

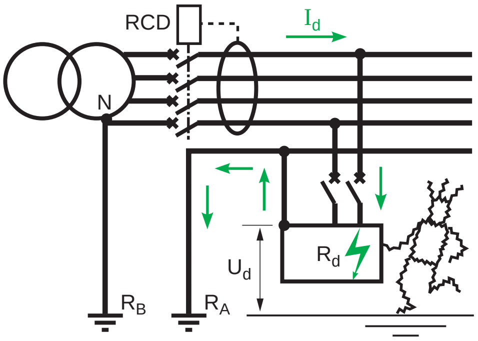


Fig. 3 : Insulation fault with TT system.
With a 400 V/230 V line supply, R_A and R_B of 10 Ω, the contact voltage Ud is 115 V!

TN system

The principle of this system, known as “connected to neutral”, is that any insulation fault will trigger a single-phase short-circuit between phase and neutral. 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 separate protective earth (PE) and neutral (N) conductors with the TN-S earthing system (S = **S**eparate conductors), see Figure 2b
  - Via a common protective earth and neutral (PEN) conductor with the TN-C earthing system (C = **C**ommon protective earth and neutral conductor), see Figure 2c.

The fault current is equivalent to a phase/neutral short-circuit. It generates a dangerous contact voltage (see **Fig. 4**). The circuit-breaker must therefore be tripped by means of “short time delay” protection or a magnetic trip release (SCPD: Short Circuit Protection Device).

The TN system allows the use of the usual overcurrent protection devices to protect against insulation faults by tripping on the first fault.

The use of RCDs avoids the need to check the value of the current if there is a fault, although they are totally unsuitable and must not be used on the TN-C system.

The TN-C system is not recommended for supplying electronic devices due to the possible circulation of harmonic currents in the neutral conductor (this subject is discussed later in this document).

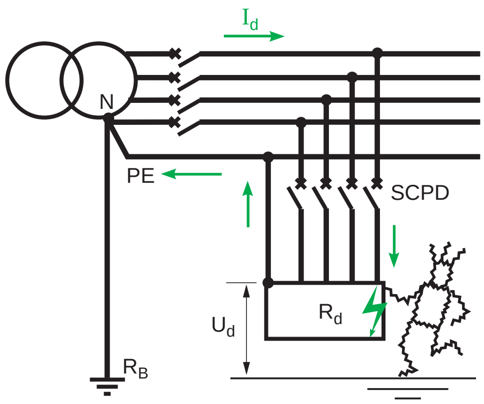


Fig. 4 : Insulation fault on a TN-S system

IT system

In this type of system, known as “unearthed neutral”, the transformer neutral is:

- Either isolated from the earth (unearthed neutral)
- Or high-impedance earthed (impedance-earthed neutral)

All frames in the installation are earthed (see Fig. 2d).

In the IT system, although the first insulation fault does not require breaking to take place, this fault must be detected using a permanent insulation monitor (PIM) and eliminated. If it is not, a second fault on another live conductor will generate a short-circuit between the live conductors concerned (see **Fig. 5**). Tripping is therefore necessary to eliminate the dangerous contact voltage. Under normal circumstances, overcurrent protection devices are used to trip the circuit and in some cases, depending on the configuration of the line supply, RCDs, which protect interconnected groups of frames.

By observing this obligation to locate and eliminate the first fault, the IT system provides the best continuity of service.

Distribution of the neutral is not recommended in IT systems. In actual fact, in the case of the first fault (maintained), the phase-earth voltage on the healthy phases is equal to the phase-to-phase voltage. The single-phase devices connected to these phases are therefore subject to phase-frame insulation voltages, which are greater than normal and may damage them (e.g. power supply for IT equipment).

If the neutral is not distributed, the connection of single-phase devices between phase and neutral is prohibited, thereby eliminating this risk. Otherwise, devices must be specified for an insulation voltage equal to the value of the phase-to-phase voltage.

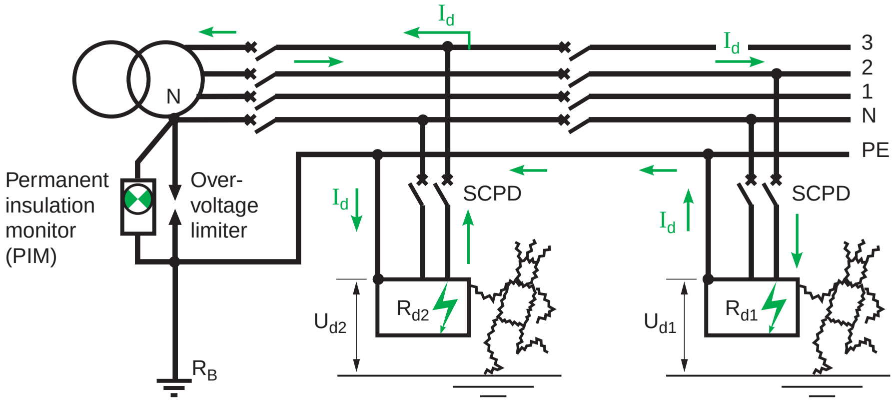


Fig. 5 : Fault current in the event of a double fault with the IT earthing system and dangerous voltages U_{d1} and U_{d2}

1.4 Short-circuit between phase and neutral

The calculation for the short-circuit current between phase and neutral differs slightly from the calculation for the three-phase short-circuit current. The diagram in **Figure 6** illustrates the three possible types of short-circuit in an installation.

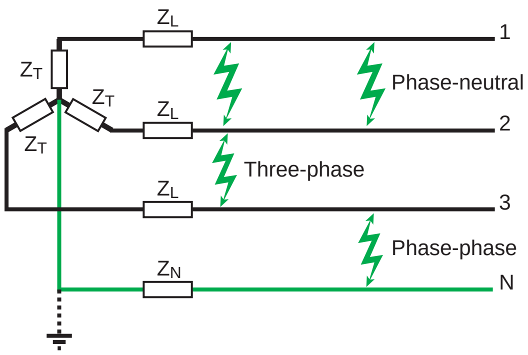


***Fig. 6** : Possible types of short-circuit on a three-phase line supply*

Where

V: Phase voltage (phase-neutral) at transformer output

U: Phase-to-phase voltage at transformer output

Z_T: Impedance of one transformer winding

Z_L: Impedance of one phase conductor

Z_N: Impedance of neutral conductor

I_{sc_3}: Three-phase short-circuit current

I_{sc_ph}: Phase-to-phase short-circuit current

$I_{sc\_ph\text{-}N}$: Phase-to-neutral short-circuit current

Generally, the connection impedance of the transformer neutral is negligible and results in the following equations:

$$I_{cc\_3} = \frac{V}{(Z_T + Z_L)}$$

$$I_{cc\_ph} = \frac{U}{2\,(Z_T + Z_L)} = \frac{V\,\sqrt{3}}{2\,(Z_T + Z_L)} = \frac{\sqrt{3}}{2} I_{cc\_3}$$

$$I_{cc\_ph\text{-}N} = \frac{V}{(Z_T + Z_L + Z_N)}$$

If the phase and neutral conductors are identical, $Z_N = Z_L$, and therefore:

$$I_{cc\_ph\text{-}N} = \frac{V}{(Z_T + 2\,Z_L)}$$

For very long cable lengths, in particular in final distribution, the impedance of the transformer is negligible in comparison with the impedance of the conductors, and therefore:

$$I_{cc\_3} \approx \frac{V}{Z_L}$$

$$I_{cc\_ph} \approx \frac{\sqrt{3}}{2}\;\frac{V}{Z_L}$$

$$I_{cc\_ph\text{-}N} \approx \frac{V}{2\,Z_L}$$

This results in the following:

$$\boxed{I_{cc\_3} > I_{cc\_ph} > I_{cc\_ph\text{-}N}}$$

2 Conventional rules for dimensioning and protecting the neutral

The majority of the rules and information described in this section have been taken from IEC 60364 and NF C 15-100, which are design and development standards for LV installations.

2.1 Neutral conductor cross-sectional area

In sinusoidal operation, the current in the neutral conductor is determined by the unbalance between the single-phase loads connected between phases and neutral.

Balanced loads: The current in the neutral conductor is zero (see **Fig. 7**).

Unbalanced loads: The current in the neutral conductor is not zero, as illustrated in **Figure 8** next page.

In the event of unbalanced loads of the same type, the current in the neutral conductor is less than or equal to the highest phase current (see **Fig. 9** next page).

In the event of unbalanced loads of different types on each phase (resistive, inductive, capacitive), the neutral current may be greater than the current in each of the phases. However, this scenario is rare in practice.

Moreover, the presence of harmonics (discussed in the following section) in the neutral conductor is also an important factor for determining the cross-sectional area of the conductor.

The **cross-sectional area of the neutral conductor**, defined as a function of the current conducted, may be:

- Smaller than the cross-sectional area of the phase conductors… if the following conditions are met simultaneously:
  - ☐ The cross-sectional area of the phase conductors must be greater than 16 mm^2 (copper) or 25 mm^2 (aluminum).
  - ☐ The cross-sectional area of the neutral conductor must be at least equal to 16 mm^2 (copper) or 25 mm^2 (aluminum).
  - ☐ The loads supplied with power during normal operation are assumed to be balanced, with a third harmonic ratio of less than 15%.
  - ☐ The neutral conductor must be protected against overcurrents.

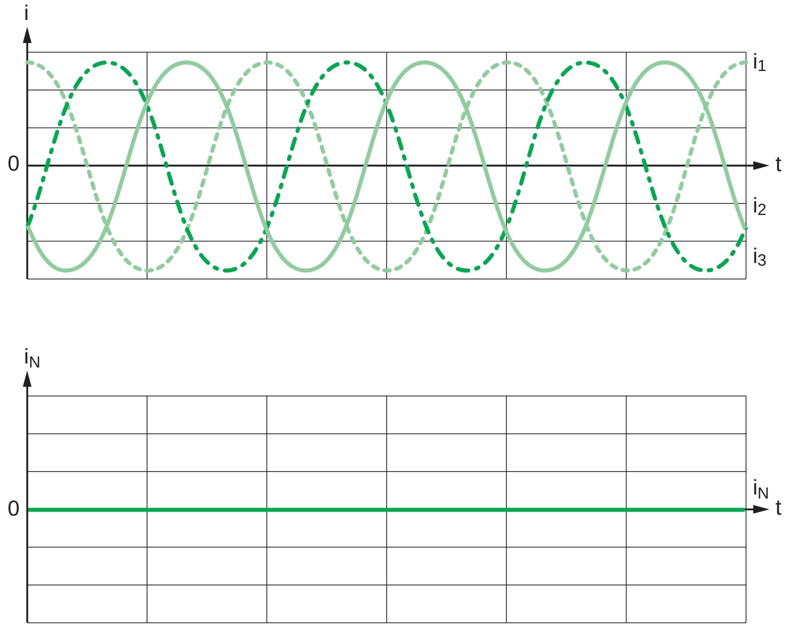


Fig. 7 : Phase currents and neutral current with balanced linear loads

A common technique is to use a neutral conductor with a cross-sectional area “half” that of the cross-sectional area of the phase conductors.

- Equal to the cross-sectional area of the phase conductors: This is the general case, in particular in single-phase circuits with 2 conductors, or when the cross-sectional area of the phase conductors is less than 16 mm^2 (copper) or 25 mm^2 (aluminum). It is equally true in the case of power supplies for non-linear loads and if the third harmonic ratio is located in the range between 15 and 33%.
- Greater than or equal to the cross-sectional area of the phase conductors in the event of power supplies for non-linear loads and if the third harmonic ratio is greater than 33%. The current in the neutral conductor is therefore a key factor in determining the cross-sectional area of the conductors.

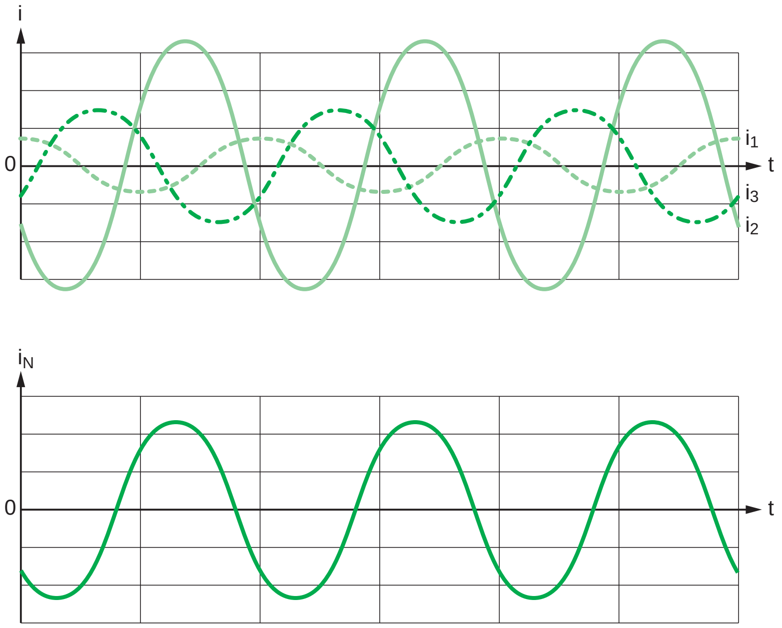


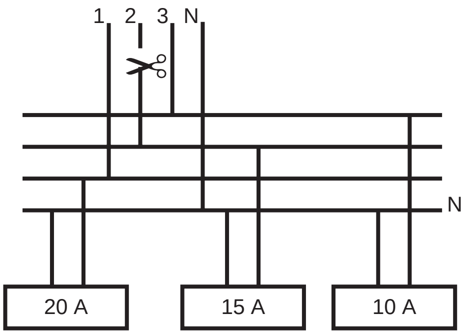
Fig. 8 : Phase currents and neutral current with unbalanced linear loads

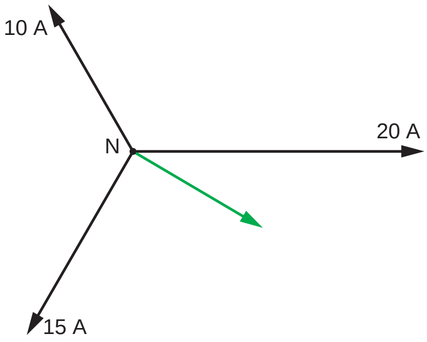
An unbalanced current circulates on a three-phase line supply due to the impossibility of achieving a permanent and perfect balance between the single-phase loads.

This current is equal to:

$$\vec{I}_N = \vec{I}_1 + \vec{I}_2 + \vec{I}_3$$

It may be very variable, as shown in the example below.





It may even be greater than the phase current if phase 2 is disconnected:

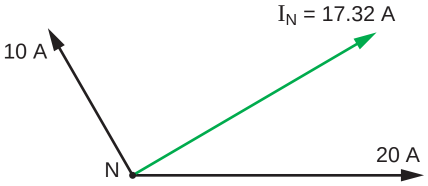


Fig. 9 : Significance of unbalanced currents in the neutral conductor

2.2 Neutral conductor disconnection

The rules for the disconnection or maintaining of the neutral conductor are designed to limit the risks of electrocution, which accompany an increase in potential.

TN-C system

The neutral conductor is also the protective earth (PEN). It is therefore essential that its continuity is maintained under all circumstances. For this reason, no breaking devices may be connected to it.

TT or TN-S system

The neutral is earthed at the installation supply point. Under normal conditions, its potential is similar to the earth potential. However, for a variety of reasons, the potential of the neutral conductor may deviate significantly from the earth potential and reach dangerous voltages in relation to earth.

A possible scenario is illustrated in **Figure 10**. The current circulating in the neutral conductor causes the neutral potential to increase on one load, even if this load is not connected to the phase following an operation or a trip. Moreover, as cable inversion between phase and neutral on one load is always a possibility, the non-breaking of one of the polarities actually risks the phase voltage applied to the load being maintained.

The simultaneous disconnection of phase and neutral is therefore recommended.

In addition, in the event of a fault in one part of the installation (accidental disconnection of neutral conductor upstream, increase in impedances, MV/LV fault, lightning strike on low-voltage lines, etc.), the potential of the neutral for user loads may rise abruptly to reach dangerous levels.

These risks are particularly inherent on the floors of multi-storey buildings, where it is more difficult to ensure the quality of earthing systems due to the exceptionally long cables. An extreme case in which the neutral potential in relation to earth was 80 V in normal operation has already been measured on one installation. This presents a risk of electrocution.

In order to avoid creating dangerous situations, the stringent application of the neutral disconnection rule is strongly recommended.

IT system

The potential of the neutral conductor may be at any level, even if it is generally close to the earth potential. If a fault is pending (e.g. phase-to-earth), the potential of the neutral in relation to earth may increase until it reaches the level of the phase voltage. Even when carrying out maintenance work on a part of the installation, which is supposed to have been disconnected from the power supply and is therefore not dangerous, personnel may still be at risk if the neutral conductor has not been disconnected. This is why it is imperative to disconnect the neutral in all cases. Only by disconnecting the neutral is it possible to ensure that the potentials between the frame and earth will be equal following tripping.

Important recommendations

- **The neutral must never be disconnected alone**: It must be disconnected after the phases and reconnected before the phases.

Failure to observe this rule will lead to overvoltages on single-phase devices in unbalanced three-phase operation, as the phase-to-phase voltage can be applied to a circuit designed to be supplied with power via the phase voltage (phase-to-neutral). This risk is illustrated in **Figure 11** next page.

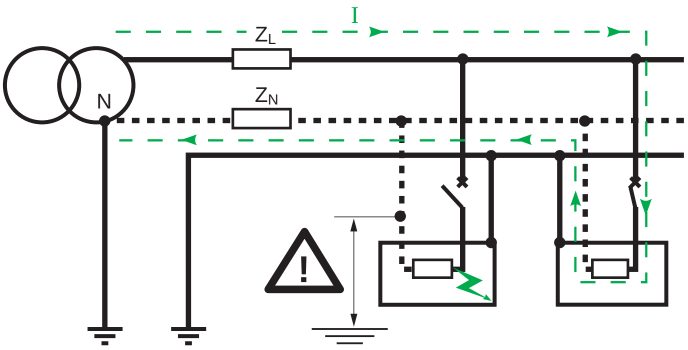


Fig. 10 : Increase in neutral potential

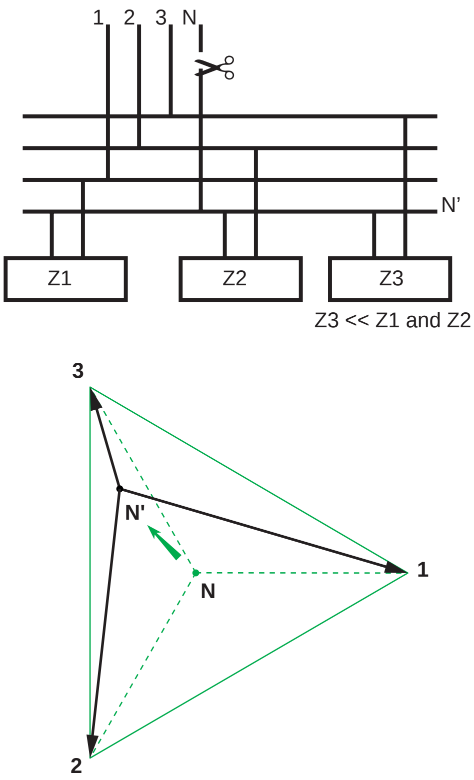


Fig. 11 : Risk of overvoltage in the event of the neutral conductor tripping

If the load connected between phase 3 and neutral is much larger than the loads on the other phases (1 and 2), the artificial neutral point N’ will be set to a potential similar to that of phase 3 if the neutral conductor trips. The loads connected between phases 1, 2 and N’ will therefore be subject to voltages V1N’ and V2N’, close to V13 and V23.

The use of multi-pole devices is therefore strongly recommended to disconnect or isolate the neutral in order to avoid the individual isolation of the neutral or breaking via single-pole devices (see IEC 60364).

In addition, due to the prevailing voltages, the breaking device for the neutral conductor will have to exhibit the necessary characteristics for isolation, in particular a sufficient insulation voltage (e.g. resistance to a 12.3 kV surge at LV for industrial equipment, in accordance with standard IEC 60947).

- For the purpose of disconnection, **the neutral must be clearly identifiable**, which is why installation standards require the conductor to be light blue in color and terminals and diagrams to bear the letter N.

Note: In an electrical distribution system without neutral, the blue conductor can be used as a phase, although this is not recommended.

Requirements regarding the position of the neutral pole in the equipment are rarely prescribed in relevant standards, except for example in France in C 62-411 for LV incoming circuit-breakers. However, it is common in many European countries, including France, to use neutral connection terminals to the left of the phase connection terminals (see **Fig. 12**).

Fig. 12 : The neutral conductor pole is to the left (Compact NS100N circuit-breaker by Merlin Gerin)

2.3 Neutral conductor protection

TN-C system

As the protective earth (PE) cannot be disconnected under any circumstances, it is not possible to disconnect the conductor (N) in a TN-C type installation in which the two conductors are combined in one (PEN).

Consequently, the cross-sectional area of the neutral will be selected accordingly since protection via automatic disconnection is not applicable.

TT or TN-S system

In the event of an overload or phase-neutral short-circuit on a given feeder, the same fault current will flow through the phase and neutral conductors. There are two possible scenarios:

- Cross-sectional area of the neutral equal to the cross-sectional area of the phases

Protection of the neutral is not obligatory. The neutral conductor is protected by the protective device for the phase conductor.

- Cross-sectional area of the neutral smaller than the cross-sectional area of the phases

A protective device to guard against overloads dimensioned according to the cross-sectional area of the neutral conductor is obligatory.

IT system

Double faults (one on a phase and the other on the neutral), may affect feeders with different ratings (connected by the faults).

Protecting the individual phases is not an entirely reliable solution: The protection for a phase with a higher rating on one feeder may not be suitable for the cross-sectional area of the neutral on the other feeder.

Provision for the protection and disconnection of the neutral is therefore obligatory, except in specific cases (e.g. single-phase circuits, protection via RCDs, etc.).

2.4 Equipment suitable for disconnecting and protecting the neutral conductor

If the above conditions have been fulfilled and if the neutral is clearly labeled, it is possible - even recommended for economical reasons - not to protect it. In all other cases, the risks of phase/neutral inversion justify protecting the neutral conductor.

Fuses

Except in very specific cases (use of fuse cartridges with strikers connected to a breaking device), the blowing of a fuse located in a live conductor will not cut off the current in the other live conductors: the break is single-pole. In order to avoid only the neutral being disconnected, it must never be protected by a fuse.

Equally, the neutral conductor will not be disconnected automatically if a fuse on one of the phases blows.

Circuit-breakers

2-pole (phase/phase or phase/neutral) or 4-pole equipment can be used to disconnect the phases and the neutral simultaneously in order to cut off the power supply to a circuit.

Phase/neutral devices on which only the phase is protected are less expensive and more compact, although the neutral must be clearly labeled (see **Fig. 13**).

RCDs

RCDs are considered a very reliable means of ensuring the operation of an electrical installation: They help to protect against direct and indirect contact as well as providing protection against fire.

Moreover, RCDs will continue to operate in the event of a phase/neutral inversion.

Because RCDs combine all these functions in a single device, their use is recommended both in new installations and in extensions to existing installations.

Emergency breaking devices

In order to ensure that the power supply to a circuit can be cut off quickly, multi-pole breaking (of all live conductors including the neutral) is recommended via the breaking device or emergency stop.

Control and monitoring

For equipment (contactors, remote control switches, circuit-breakers, load-shedding devices, regulators, etc.) not designed for protection purposes but used for controlling or monitoring loads (machines, lighting), standards do not require the disconnection of the neutral. However, when auxiliary contacts on protective devices are used to set up logic or signaling functions, it is sometimes difficult to predict the potential of each of the conductors in the event of a fault (in particular on a three-phase system). In this case, disconnection of the neutral is recommended.

Fig. 13 : "Déclic" phase-neutral circuit-breaker with identification of neutral pole (by Merlin Gerin)

3 And now for harmonics…

3.1 Single-phase non-linear loads

An increasing amount of electricity is being consumed by single-phase non-linear electronic loads (fluorescent lighting with electronic ballast, domestic electrical appliances, IT equipment, variable speed drives, etc.).

These devices generally have a switch mode power supply, for which the most common incoming system is a single-phase diode rectifier with capacitive filtering (see **Fig. 14**).

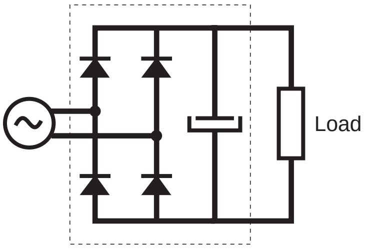


Fig. 14 *: Single-phase rectifier with capacitive filtering*

The current drawn by these loads comprises positive and negative pulses synchronized with peaks in the line supply voltage. Therefore, its third harmonic component may reach 85% of the fundamental.

The waveform of the current and its typical harmonic spectrum are illustrated in **Figures 15** and **16**.

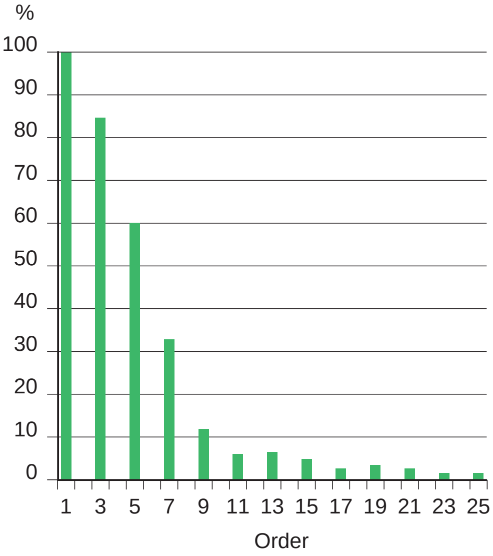


Fig. 16 *: Harmonic spectrum. Here, the Total Harmonic Distortion of the phase current (THD) is 110% and the third harmonic ratio (i_3) is 85%*

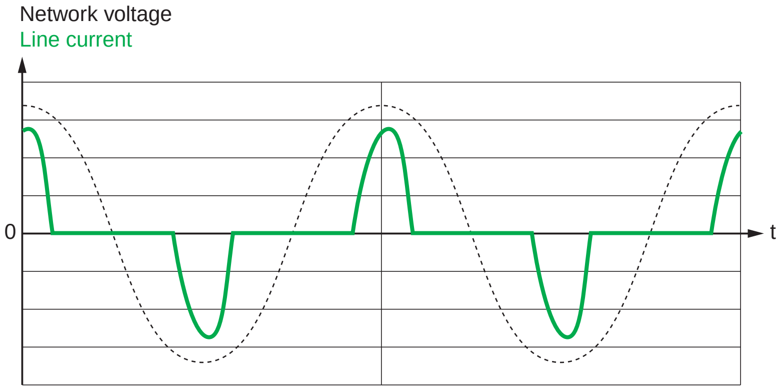


Fig. 15 *: Shape of the current*

The table in **Figure 17** lists examples of single-phase devices that can generate harmonic currents, along with the most important typical characteristics.

Type of device	**P (W)**	**I_L (A)**	**i_3 (%)**
PC	60	0.5	85
PC with active printer	300	1.45	35
Photocopier in standby mode	70	0.32	65
Photocopier active	1500 - 2200	7 - 10	15
Fluorescent tube with magnetic ballast	36	0.2	25
Fluorescent tube with electronic ballast	36	0.16	10
Fluorescent bulb	250	1.4	10
Compact fluorescent lamp	25	0.2	80
Variable speed drive	500 - 3000	4 - 18	80

P (W): Active power consumed
I_L (A): rms value of current drawn
i_3 (%): Third harmonic current ratio

Fig. 17 : The main generators of third harmonic currents in industrial and commercial installations

3.2 Single-phase loads in a three-phase system

Let's consider two specific scenarios in a simplified system comprising a balanced three-phase source and three identical single-phase loads, connected between phase and neutral (see **Fig. 18**):

- Three linear loads
- Three non-linear loads

- In the case of **linear loads**, the currents form a balanced three-phase system. The sum of the phase currents is therefore zero, as is the neutral current.

- In the case of **non-linear loads**, the phase currents are non-sinusoidal and therefore contain harmonics, in particular of orders that are multiples of 3.

As all three-phase currents are equal, the third order harmonic currents, for example, have the same magnitude and can be written as follows:

$$i_{r3} = I_3 \sin 3\ (\omega t)$$

$$i_{s3} = I_3 \sin 3\left(\omega t - \frac{2\pi}{3}\right) = I_3 \sin(3\omega t - 2\pi) = i_{r3}$$

$$i_{t3} = I_3 \sin 3\left(\omega t - \frac{4\pi}{3}\right) = I_3 \sin(3\omega t - 4\pi) = i_{r3}$$

In this example, the **third order harmonic currents in all three phases are identical**.

As the current in the neutral is equal to the sum of the currents in the phases, the third order component of the neutral current is therefore equal to the sum of the third order components, i.e.: $i_{n3} = 3\ i_{r3}$

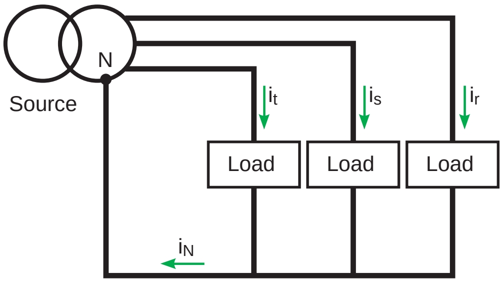


Fig. 18 : Single-phase loads

As a general rule, for balanced loads, harmonic currents, which orders are a multiple of 3, are in phase and are added up arithmetically in the neutral conductor, whereas fundamental components and harmonics of orders that are not multiples of 3 cancel one another out.

Third order currents are therefore zero-sequence currents, circulating in phase in all three phases.

3.3 Current in the neutral conductor in a three-phase system

Figure 19 shows a number of curves representing the currents circulating in the phases of three identical non-linear single-phase loads, as described in Section 3.1 and connected between phases and neutral. The resulting current in the neutral conductor, which is the sum of the three phase currents, is also shown.

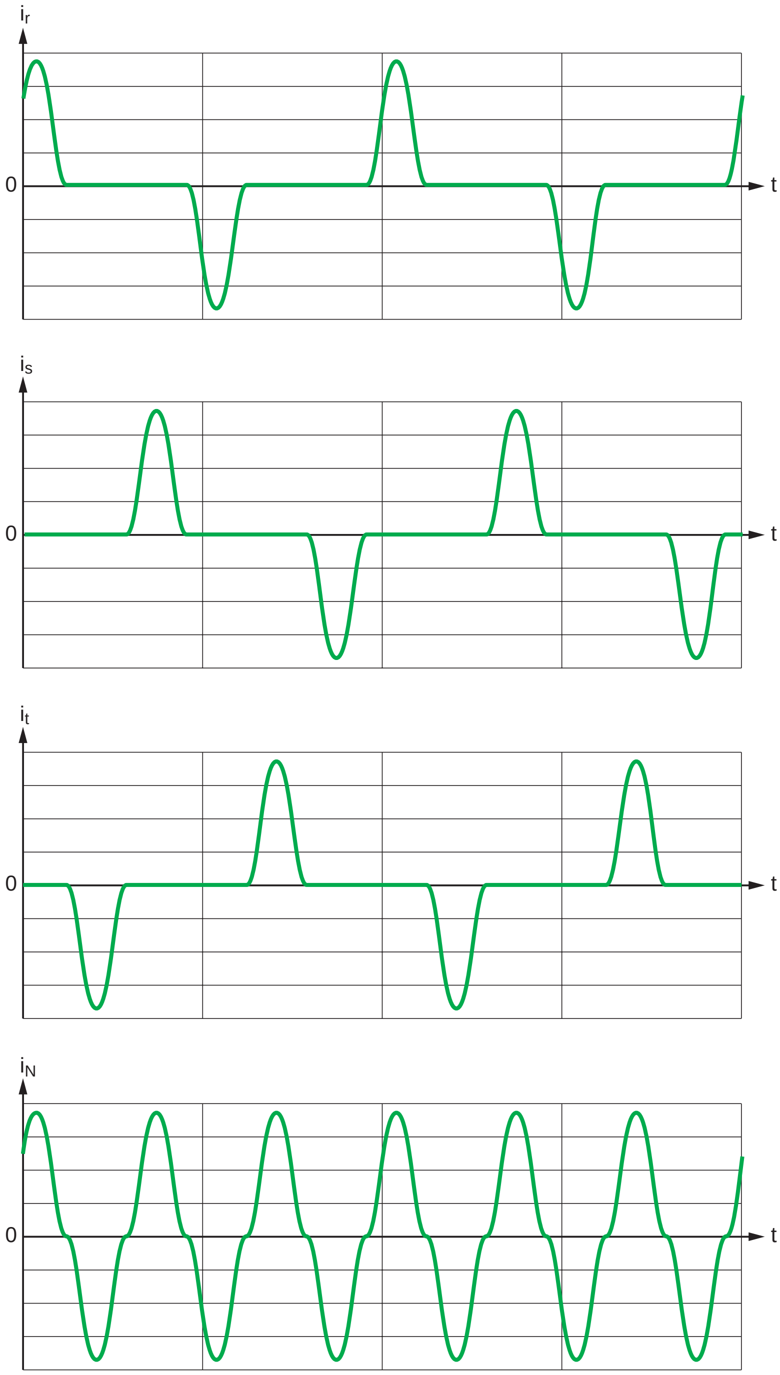


Fig. 19 *: Phase and neutral currents supplying 3 identical non-linear single-phase loads*

The harmonic spectra of the phase and neutral currents are shown in **Figures 20** and **21**.

These diagrams show that the neutral current only contains odd order components that are multiples of 3 (i.e. 3, 9, 15, etc.), whose magnitudes are 3 times greater than those of the phase currents. Of course, the third harmonic is dominant and other components of orders of multiples of 3 (i.e. 9, 15, etc.) have very little effect on the rms value.

The neutral current is therefore almost equal to 3 times the third harmonic current of each phase, i.e.: $I_N \approx 3\ I_3$

The neutral current referred to here is the result of the combination of the currents in the single-phase circuits. In electrical installations, this therefore primarily concerns distribution systems (three-phase to single-phase) and devices installed on the incoming supply.

This phenomenon only affects three-phase circuits, as phase and neutral currents in single-phase circuits are of course identical.

Calculating the maximum rms value of the neutral current

Let's suppose, as in Figure 19, that the current waves of the 3 phases do not overlap.
For a period T of the fundamental, a phase current consists of a positive wave and a negative wave separated by an interval during which the current is zero.

The rms value of the line current can be calculated using the formula:

$$I_L = \sqrt{\frac{1}{T}\int_0^T i_l^2 dt}$$

The rms value of the neutral current can be calculated over an interval equal to T/3.
During this interval, the neutral current also consists of a positive wave and a negative wave, identical to those of the phase current.
The rms value of the neutral current can therefore be calculated as follows:

$$I_N = \sqrt{\frac{1}{T/3}\int_0^{T/3} i_n^2 dt}$$

$$I_N = \sqrt{3}\ \sqrt{\frac{1}{T}\int_0^{T/3} i_n^2 dt}$$

And as: $\int_0^{T/3} i_n^2 dt = \int_0^{T} i_l^2 dt$

so: $I_N = \sqrt{3}\ \sqrt{\frac{1}{T}\int_0^{T} i_l^2 dt} = \sqrt{3}\ I_L$

Therefore, the current in the neutral conductor has an rms value $\sqrt{3}$ times greater than that of the current in a phase.

When the current waves of all 3 phases overlap (see **Fig. 22** and **23** next page), the rms value of the current in the neutral is less than $\sqrt{3}$ times the rms value of the current in a phase.

Similarly, when the loads constitute part of the linear circuit, the current drawn is not equal to zero (see **Fig. 24** next page) and the description above does not apply. The rms value of the current in the neutral is therefore strictly less than $\sqrt{3}$ times the rms value of the current in a phase.

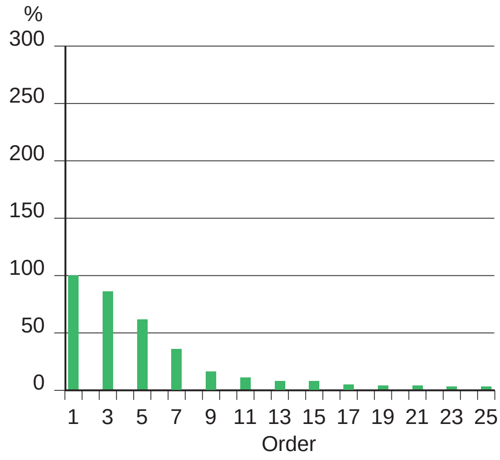


***Fig. 20** : Phase current spectrum*

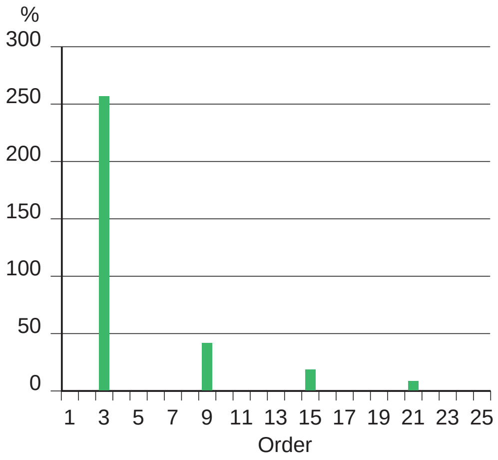


***Fig. 21** : Neutral current spectrum*

The factor $\sqrt{3}$ can therefore only be obtained if power is being supplied exclusively to loads that are identical on all 3 phases, such as those described in Section 3.1. As the power of these devices is relatively low (usually several tens of W each), this can therefore only affect low-current feeders. The neutral current may therefore exceed the phase current, but only on low-load feeders. The capacity of the neutral conductor will therefore not be exceeded if its cross-sectional area is equal to that of the phases.

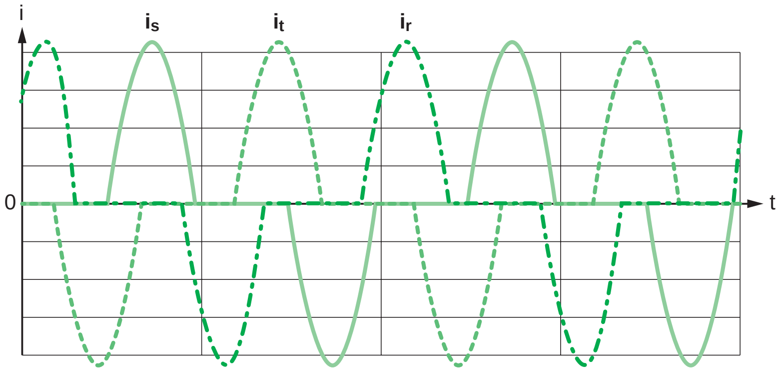


***Fig. 22** : Currents in the 3 phases, with overlap*

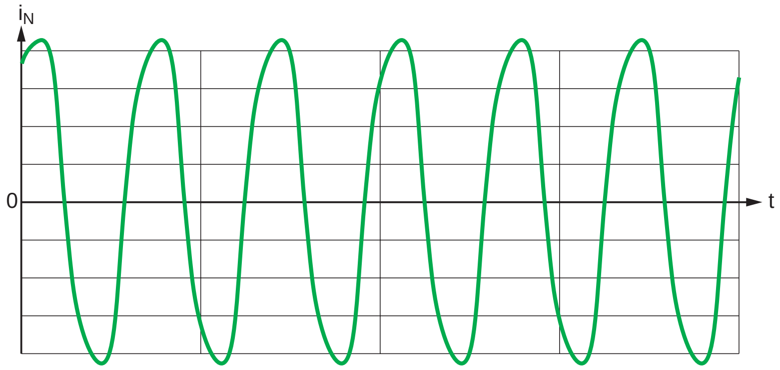


***Fig. 23** : Current in the neutral, with overlap*

***Fig. 24** : Current drawn by a load with linear and non-linear circuits*

3.4 Loading of the neutral conductor

The current in the neutral may therefore exceed the current in each phase in installation such as those with a large number of single-phase devices (IT equipment, fluorescent lighting). This is the case in office buildings, computer centers, Internet Data Centers, call centers, banks, shopping centers, retail lighting zones, etc.

This is not a general situation, due to the fact that power is being supplied simultaneously to linear and/or three-phase loads (heating, ventilation, incandescent lighting, etc.), which do not generate third order harmonic currents. However, particular care must be taken when dimensioning the cross-sectional areas of neutral conductors when designing new installations or when modifying them in the event of a change in the loads being supplied with power.

A simplified approach can be used to estimate the loading of the neutral conductor.
As shown in 3.3, for balanced loads, the current in the neutral I_N is very close to $3\ I_3$, i.e.:

$I_N \approx 3\ I_3$

This can be expressed as:

$I_N \approx 3\ i_3\ I_1$

For low distortion factor values, the rms value of the current is similar to the rms value of the fundamental, therefore:

$I_N \approx 3\ i_3\ I_L$

and

$I_N / I_L \approx 3\ i_3$ (%)

This equation simply links the overloading of the neutral (I_N / I_L) to the third harmonic current ratio. In particular, it shows that when the loading reaches 33%, the current in the neutral conductor is equal to the current in the phases.

Whatever the distortion value, it has been possible to use simulations to obtain a more precise law, which is illustrated in **Figure 25** .

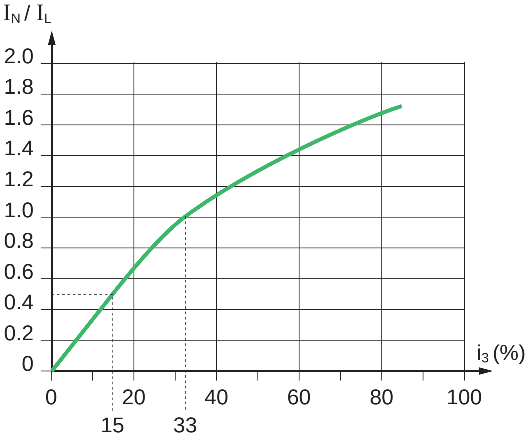


Fig. 25 : Loading of the neutral conductor based on the third harmonic ratio

In the absence of detailed information about harmonic emissions on the installed devices, another simplified approach is to link the loading of the neutral conductor directly with the percentage of electronic loads.
The graph in **Figure 26** is based on a third harmonic current ratio generated by electronic loads equal to 85%.

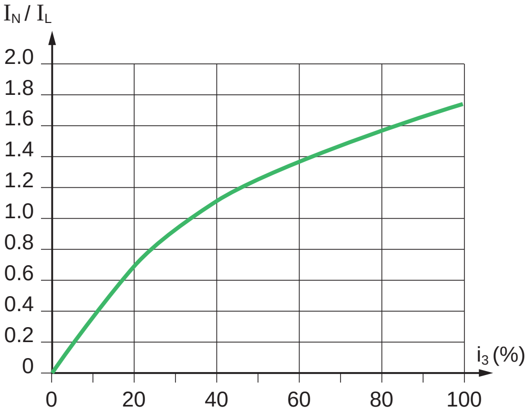


Fig. 26 : Overload of the neutral conductor based on the percentage of non-linear loads

In high-power installations (order of magnitude P > 100 kVA or I > 150 A), a number of factors contribute to reducing the overloading of the neutral:

- An increasing number of IT equipment (workstations, servers, routers, ASI, etc.) is using PFC (Power Factor Correction) circuits to significantly reduce the third harmonics generated.
- HVAC installations in large buildings are using three-phase power supplies (and therefore do not contribute to the generation of third harmonics).
- Fluorescent lighting equipment (with magnetic or electronic ballasts) generates proportionally fewer third harmonics, partially compensating the harmonics generated by IT equipment.

The higher the power of the installation, the greater this proliferation of loads. Other than in exceptional cases, the harmonic ratio in these installations does not exceed 33% and the current in the neutral conductor does not exceed the current in the phases. It is therefore not necessary to overdimension the neutral conductor in relation to the phase conductors (single-pole conductors).

3.5 How harmonic currents affect electrical trunking

The circulation of harmonic currents causes an additional temperature rise in electrical trunking for various reasons:

- The circulation of harmonic currents causes a rise in temperature in the neutral conductor, although no current usually flows through this conductor in balanced sinusoidal operation.
- The circulation of harmonics of all orders causes an additional temperature rise in all conductors due to increased skin effect and eddy current losses.

In the case of busbar trunking, it has been possible to determine the derating factor to be applied by measuring temperature rise.

Figure 27 shows the maximum permissible currents in the phase and neutral conductors as a function of the harmonic ratio ($I_{max} = k.I_{nominal}$).

For example, the maximum permissible currents in a system with a rating of 1000 A with circulation of harmonic currents such as i_3 = 50% is:

- Maximum phase current: 770 A
- Maximum neutral current: 980 A

The trunking rating should of course be selected taking into account the possible current in the neutral conductor, although a trunking system in which the conductors all have the same cross-sectional area is perfectly suitable for this situation.

The use of a neutral conductor with a double cross-sectional area or made from copper instead of aluminum offers no significant improvement. In fact, the losses in the neutral conductor, even when reduced by these specific design selections, contribute significantly to the global temperature rise of the trunking. Derating is therefore still required.

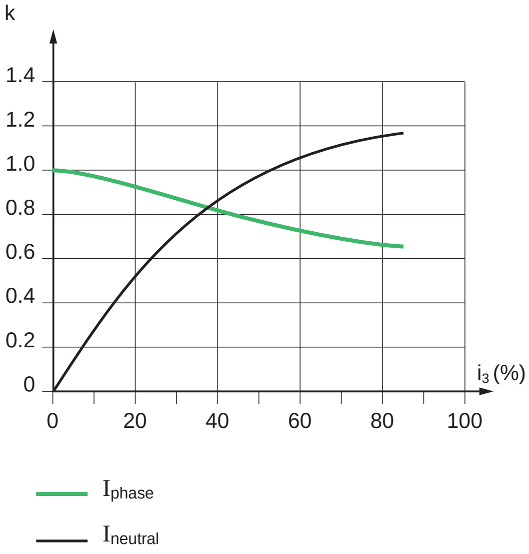


Fig. 27 *: Permissible phase and neutral currents in a busbar trunking system*

3.6 Estimating the third harmonic ratio

The cross-sectional area of the neutral conductor is determined by estimating the third harmonic ratio in the installation. As measurements cannot be taken on-site (if a new installation is being designed, for example), there are two possible approaches: one simplified, the other more complex.

Simplified approach

Use the descriptions and technical specifications of the loads connected in the installation to calculate the sum of the phase currents of all loads (single-phase and three-phase).

This sum produces I_{ph} (A).

Use the same technique to calculate the third harmonic currents of the single-phase electronic loads only.

This sum produces I_3 (A).

You can then calculate the third harmonic ratio:

$$i_3(\%) = 100\,\frac{I_3}{I_{ph}}$$

More complex approach

To obtain a more precise estimate of the third harmonic ratio, a more complex approach takes the following additional factors into account:

- Power factor of loads
- Operational coincidence factor
- Phase dispersion of third harmonic currents
- Actual spectrum of installed loads (not typical spectrum)

A detailed description of an approach of this type does not fall within the scope of this document.

Example (simplified approach)

In an office building, the loads supplied with power via the phase on each feeder are listed in the table in **Figure 28** next page. Note that for the purposes of simplification, the third harmonic current is obtained by multiplying the third harmonic ratio by the rms current (and not the fundamental current, which is usually not known).

Type of load	**Number**	**rms current drawn per unit (A)**	**Total rms current (A)**	**Third harmonic ratio (%)**	**Total third harmonic current (A)**
PC	10	0.5	5	85	4.25
PC + printer	5	1.45	7.3	35	2.55
Photocopier in standby mode	2	0.32	0.64	65	0.42
Fluorescent tubes with magnetic ballast	20	0.2	4	25	1
Heating		10	10	0	0
Total			**27**		**8.2**

Fig. 28 *: Load supply currents in an office building*

The calculation produces a global third harmonic ratio of:

$$i_3(\%) = 100 \times \frac{8.2}{27} = 0.30$$

Note:
An increased third harmonic ratio (> 33%) may occur in a zone in which a number of identical devices are supplied with power via the same line, for example the power supply for a PC network.

In this zone, the neutral current may therefore exceed the phase current.

However, if the distribution panel and conductors upstream have been dimensioned for a greater power rating, the risk of overloading the neutral at this level is negligible.

If, in the previous example, the installation is rated at 40 A, the third harmonic ratio for this current value will not exceed 20%.

3.7 Dimensioning the components in an installation

The third harmonic ratio has an impact on the current in the neutral and therefore on the capacity of all components in an installation:

- Distribution panels
- Protection and distribution devices
- Cables and trunking systems

According to the estimated third harmonic ratio, there are three possible scenarios: ratio below 15%, between 15 and 33% or above 33%.

Third harmonic ratio below 15% ($i_3 \leqslant 15\%$)

The conductor is considered not to be carrying current.

The cross-sectional area of the phase conductors is determined solely by the current in the phases.

The cross-sectional area of the neutral conductor may be smaller than the cross-sectional area of the phases if the cross-sectional area is greater than 16 mm^2 (copper) or 25 mm^2 (aluminum).

Protection of the neutral is not obligatory, unless its cross-sectional area is smaller than that of the phases.

Third harmonic ratio between 15 and 33% ($15 < i_3 \leqslant 33\%$)**, or in the absence of any information about harmonic ratios**

The conductor is considered to be carrying current.

The operating current of the multi-pole trunking must be reduced by a factor of 0.84 (or, conversely, select trunking with an operating current equal to the current calculated, divided by 0.84).

The cross-sectional area of the neutral MUST be equal to the cross-sectional area of the phases.

Protection of the neutral is not necessary.

- Example calculation for a busbar trunking system
  - Dimensioning hypothesis:

Phase current calculated = 1000 A

Third harmonic ratio (i_3) = 20%

Neutral current calculated (for i_3 = 20%) = 600 A (see Figure 25).

In this case, the rating of the busbar trunking system is determined as a function of the operating current in the phases ($I_{ph} > I_N$).

Operating current of suitable trunking = 1190 A (= 1000 A/0.84).

  - Selection of busbar trunking and protective measures

Rating of suitable trunking = 1250 A

(1st cataloged rating > 1190 A)

Rating of protective circuit-breaker = 1250 A (same as trunking rating)

The trip threshold for phase and neutral overload is set at the calculated phase current value, i.e. 1000 A.

Note: The factor 0.84 is taken from standard NF C 15-100, IEC 60364-52 prescribes a factor of 0.86.

Third harmonic ratios greater than 33%
($i_3 > 33\%$)

This rare case represents a particularly high harmonic ratio, generating the circulation of a current in the neutral, which is greater than the current in the phases. Precautions therefore have to be taken when dimensioning the neutral conductor.

Generally, the operating current of the phase conductors must be reduced by a factor of 0.84 (or, conversely, select trunking with an operating current equal to the current calculated, divided by 0.84). In addition, the operating current of the neutral conductor must be equal to 1.45 times the operating current of the phase conductors (i.e. 1.45/0.84 times the phase current calculated, therefore approximately 1.73 times the phase current calculated).

The **recommended method** is to use multi-pole trunking in which the cross-sectional area of the neutral is equal to the cross-sectional area of the phases. The current in the neutral conductor is therefore a key factor in determining the cross-sectional area of the conductors. Protection of the neutral is not necessary, although it should be protected if there is any doubt in terms of the loading of the neutral conductor.

This approach is common in final distribution, where multi-pole cables have identical cross-sectional areas for the phases and for neutral.

With busbar trunking systems, precise knowledge of the temperature rises caused by harmonic currents enables a less conservative approach to be adopted. The rating of a busbar trunking system can be selected directly as a function of the neutral current calculated.

- Example calculation for a busbar trunking system

□ Dimensioning hypothesis:

Phase current calculated = 1000 A

Neutral current calculated
(for $i_{h3} = 50\%$) = 1300 A (see Figure 25)

The rating of the busbar trunking system is determined as a function of the permissible neutral current ($I_{ph} < I_N$).

□ Selection of busbar trunking and protective devices

Rating of suitable trunking = 1600 A
(1st cataloged rating > 1300 A)

Rating of protective circuit-breaker = 1600 A
(same as trunking rating)

The trip threshold for phase overload is set at the calculated phase current value, i.e. 1000 A.

The neutral is not protected (circuit-breaker in 4P-3D configuration).

Another method is to use a neutral conductor with a cross-sectional area greater than that of the phases. A common solution used to extend an existing installation is to double the size of the neutral conductor (“200% neutral”). The protection and control devices (circuit-breaker, load break switches, contactors, etc.) then have to be dimensioned according to the current in the neutral.

- In the case of single-pole cables, it may be more cost-effective to select phase conductors with smaller cross-sectional areas than the cross-sectional area of the neutral conductor.

The cables can be protected using a circuit-breaker with a trip threshold on the neutral greater than and proportional to the trip threshold on the phases (circuit-breakers with “oversized neutral”).

Example: 400 A circuit-breaker

Trip threshold on one phase pole = 150 to 250 A

Trip threshold on neutral pole = 250 to 400 A

3.8 Harmonics and earthing systems

In a TNC neutral point connection, a single conductor (PEN) ought to ensure the equipotentiality of the frames (i.e. their protection) in the event of an earth fault and the circulation of unbalanced currents.

In reality, the circulation of harmonic currents in this conductor poses a number of problems.

- Via the impedance of the PEN, the harmonic currents create small potential differences between devices (in the order of several volts), which may cause communication malfunctions between electronic devices.
- These currents “roam” continuously through the structures of the building at random, causing radiant interference on sensitive loads.
- The PEN cannot be protected against overloads.
- Finally, the circulation of harmonic currents in the neutral causes a voltage drop in the PEN, creating potential differences between the frames connected to the PEN and potentially posing a risk.

The TNC neutral point connection must therefore only be used for power circuit power supplies, at the supply end of the installation, and is obligatory for power supplies for sensitive loads (IT equipment for example) with circulation of harmonic currents.

3.9 How to manage harmonics affecting the neutral

A number of measures can be taken to eliminate or reduce the effects of harmonic currents, in particular third harmonic currents.

Modifications to the installation

The most common solutions for avoiding neutral conductor overload are as follows:

- Use a separate neutral conductor for each phase. This solution is rarely used because it is expensive.
- Double the neutral conductor. As the current in the neutral cannot exceed 1.73 times the current in each phase, this is an easy solution to implement in existing systems.
- Use trunking with ratings suitable for the current in the neutral, which may be the dominant current. (See Section 3.5.)

Star-delta transformer

This configuration is used frequently in electrical distribution in order to eliminate the circulation of third harmonic currents in distribution and transmission networks.

Note that third harmonic currents can only be totally eliminated if the secondary loads are perfectly balanced. Otherwise, the third harmonic currents in the 3 phases are not equal and cannot be compensated in full at the vertices of the triangle.

Transformer with zigzag secondary

This configuration is also used in distribution and can have the same effect as the star-delta transformer configuration.

Note that third harmonic currents can only be totally eliminated if the loads are perfectly balanced. Otherwise, the third harmonic currents in the three phases are not equal and the ampere-turns on a single core at the secondary cannot be compensated in full. A third order harmonic current can therefore circulate in the primary winding, and therefore in the power supply line.

Reactance with zigzag connection

The simplified schematic for this reactance is illustrated in **Figure 29** .

As in the case of a zigzag transformer, it is easy to see from this figure that the ampere-turns on a single core cancel one another out. As a result, the impedance seen by the third order harmonic currents is very low (leakage inductance of the winding only). The zigzag reactance therefore produces a return path with low impedance to zero-sequence currents and harmonics of the third order and multiples of 3. It therefore reduces the current circulating in the power supply neutral, as illustrated in **Figure 30** , for single-phase loads.

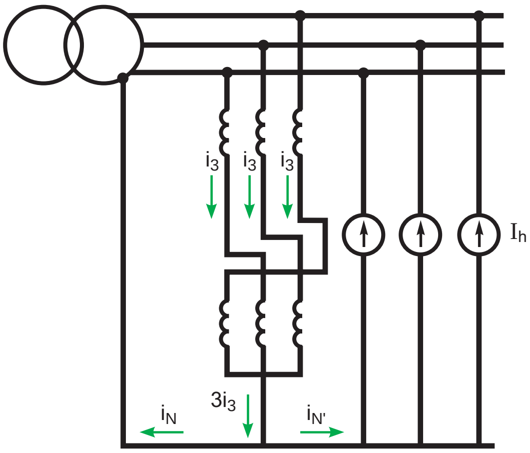


Fig. 29 *: Zigzag reactance*

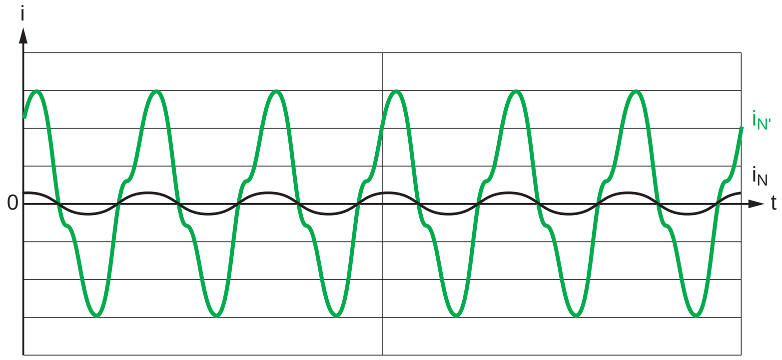


Fig. 30 *: Neutral currents* i_N *with and* $i_{N'}$ *without use of a zigzag reactance*

Third order filter in the neutral

The principle of this device consists of placing a trap circuit tuned to the third harmonic in series with the neutral conductor (see **Fig. 31**).

Figure 32 illustrates the waveforms obtained, assuming that single-phase loads of the type described in Section 3.1 are connected between phase and neutral.
The reduction in the neutral current is accompanied by an increase in voltage distortion, although this does not generally affect the operation of standard IT equipment.

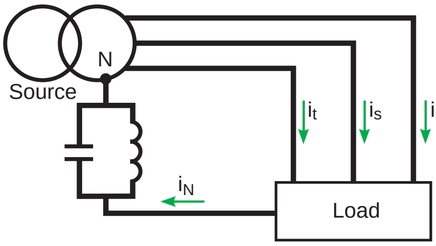


Fig. 31 : Third order filter in the neutral

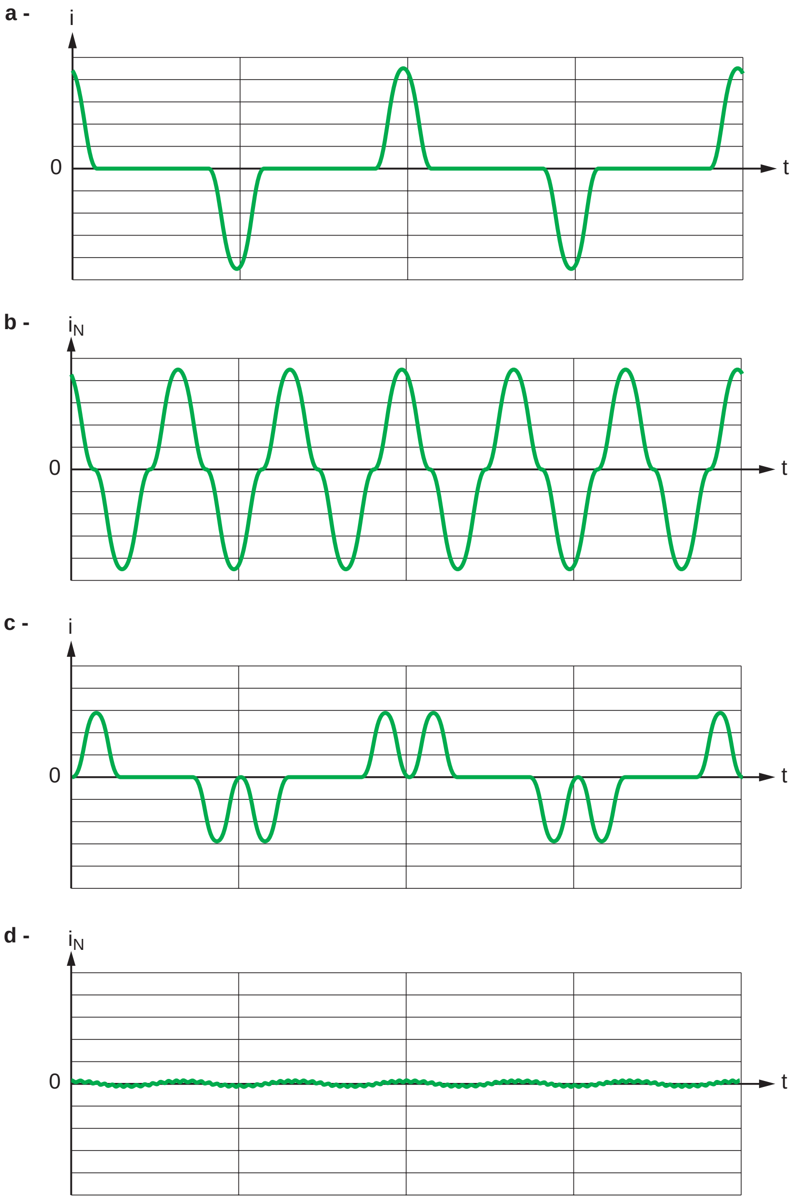
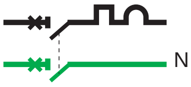
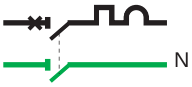
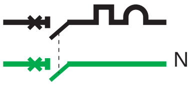
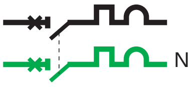
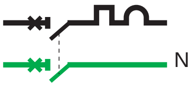
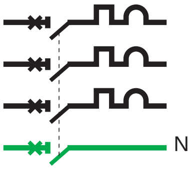
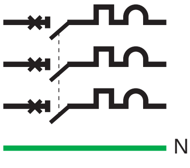
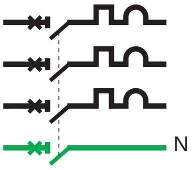
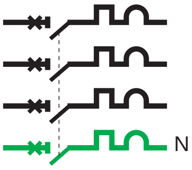
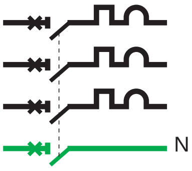
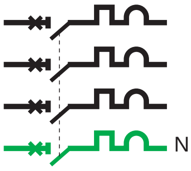
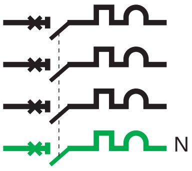
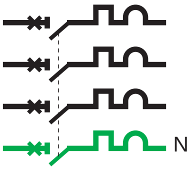
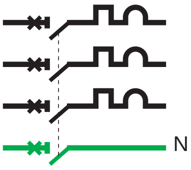


*Fig. 32 : Waveforms: Line current **[a]** and neutral current **[b] without** filter;*
*line current **[c]** and neutral current **[d] with** filter*

4 Summary

The table in **Figure 33** lists the various possible scenarios in which a neutral conductor is used.

Sn: Neutral cross-section area
Sph: Phase cross-section area

	TT	**TN-C**	**TN-S**	**IT**
Single-phase P-N	 or 			 or  (see note)
Three-phase 3P-N Sn ⩾ Sph				 or  (see note)
Three-phase 3P-N Sn < Sph				 or  (see note)

Note:

Overcurrent detection is required in the neutral unless:

- An upstream device has been installed to protect the neutral against short-circuits
- The neutral is protected by an RCD with a trip threshold less than or equal to 0.15 times the permissible current in the neutral conductor.

Fig. 33 : The various situations in which the neutral conductor may appear

5 Conclusion

The neutral is a live conductor through which unbalanced currents, harmonic currents and fault currents flow. Dangerous transient voltages can occur in relation to the potential reference of the electrical installations (earth and PE).

Standardization bodies are working hard to ascertain whether or not the neutral needs to be:

- Protected
- Disconnected
- Isolated

using earthing systems.

This has resulted in the production of a large number of standards, some of which are particularly complex.

In practice, let’s keep in mind:

- The disconnection of the neutral is generally obligatory (IT and TT system) or strongly recommended (TN-S system).
- The isolation of the neutral is an essential safety factor (for all earthing systems).
- Breaking and isolating devices must ensure that all live conductors are disconnected.
- In the face of the proliferation of harmonic currents, it is often advisable to protect the neutral conductor, even if its cross-sectional area is the same as that of the phases.

Compliance with these four rules, regardless of the neutral point connection, provides a means of ensuring the protection of persons and property and avoiding any malfunction of sensitive equipment.
The TN-C system remains a specific case, as the PEN may neither be disconnected nor isolated.

Appendix 1: Reminders

Relationships between I_1, I_L and THD

By definition:

$$\text{THD} = \sqrt{\sum_{2}^{\infty} \left(\frac{I_h}{I_1} \right)^2}$$

rms value of current:

$$I_L = \sqrt{\sum_{1}^{\infty} (I_h)^2} = \sqrt{I_1^2 + \sum_{2}^{\infty} (I_h)^2}$$

So:

$$\frac{I_L}{I_1} = \sqrt{1 + \sum_{2}^{\infty} \left(\frac{I_h}{I_1} \right)^2} = \sqrt{1 + \text{THD}^2}$$

Therefore:

$$I_L = I_1 \sqrt{1 + \text{THD}^2}$$

Loading of the neutral conductor as a function of the THD (approximate calculation)

Considering that the third harmonic is the dominant harmonic, the distortion factor is very close to the third harmonic ratio. So:

$\text{THD} \approx i_3$ (%)

Moreover, as shown in Section 3.3, for balanced loads, the current in the neutral I_N is very close to $3\ I_3$.

So:

$I_N \approx 3\ I_3$ (A)

This can be expressed as:

$I_N \approx 3\ i_3\ I_1 \approx 3\ \text{THD}\ I_1$

Using the general formula:

$$I_1 = \frac{I_L}{\sqrt{1 + \text{THD}^2}}$$

we can obtain:

$$I_N \approx 3\ \text{THD} \frac{I_L}{\sqrt{1 + \text{THD}^2}} \Rightarrow \frac{I_N}{I_L} \approx \frac{3\ \text{THD}}{\sqrt{1 + \text{THD}^2}}$$

This approximate formula is only valid if the result is less than $\sqrt{3}$ and for low THD values. The loading of the neutral conductor therefore varies as a function of the distortion factor as shown in the graph below (see **Fig. 34**).

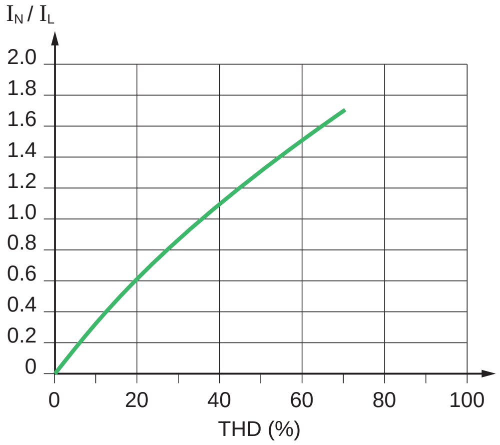


***Fig. 34** : Variation in the loading of the neutral conductor as a function of the distortion factor*

Appendix 2: The specific case of LV installations with various power supply sources

Many LV installations have various sources: transformers or emergency sets. The provision of the power supply via various sources enables continuity of service to be improved, the cost of the subscription contract to be reduced due to the removal of peak demands and makes cogeneration possible.

In most cases, these sources are used separately, although in some cases a number of sources are connected to increase power and/or availability.

Whatever the case, whether the sources are connected or not, precautions must be taken to ensure that all earth fault protective devices are operating correctly and, in this respect, the situation of the neutral is particularly important.

The information below is relevant for all installations in which the neutral would not be disconnected in particular by general circuit-breakers or section-specific switches. The two sources may be two transformers or a transformer and a generator.

Insulation fault and neutral not disconnected

In the event of an insulation fault (see **Fig. 35**), although some of the fault current (Id_1) will be restored as normal to the source via the earth or PE, some of it (Id_2) may be restored to the source via the earth and the neutral conductor.

Depending on the distribution of the currents, the protection of the source affected by the fault may not trip if its sensitivity threshold is not reached.

Conversely, the protection for the source not affected may trip if its sensitivity threshold is reached.

Note that the risk of protective devices tripping unintentionally is the same whether the section switch is open or closed.

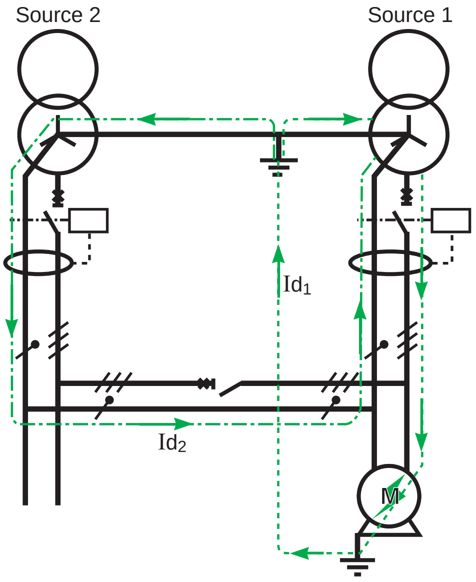


Fig. 35 *: Insulation fault with neutral not disconnected*

Connection of sources in the presence of harmonics or unbalance

Let’s now consider the two sources connected permanently without disconnection of the neutral but with the presence of third harmonics or unbalance due to single-phase loads (see **Fig. 36**).

This results in current circulating in the neutral conductor, which, due to the neutral links between the 2 sources, may loop back from one source to the other.

As well as being able to cause earth protective devices connected to the sources to trip unintentionally, this residual current generates an electromagnetic field wherever it circulates, particularly in earth conductors and the conductive structures of buildings.

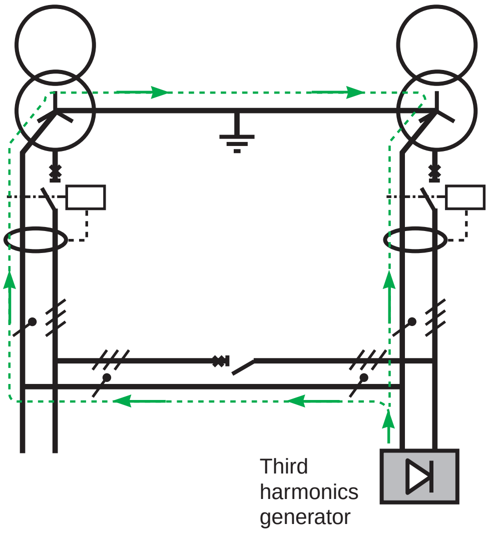


Fig. 36 *: Harmonic or unbalanced current with neutral not disconnected*

Recommendation

These problems can be avoided if all poles are disconnected on the section switch. Moreover, if this disconnection is also made on the two source circuit-breakers, it will ensure correct operation in all scenarios.

Other possible solutions include distribution without neutral at source and connection level and the use of star-delta transformers on feeders.

Appendix 3: Bibliography

Standards

- IEC 60364, NF C 15-100 : Low-voltage electrical installations.

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