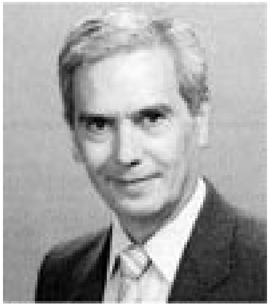
n° 173

earthing systems worldwide and evolutions

Bernard Lacroix

An ESPCI 74 engineering graduate (from the Ecole Supérieure de Physique et Chimie Industrielle de Paris), he then worked 5 years for Jeumont Schneider, where his activities included development of the TGV chopper.
After joining Merlin Gerin in 1981, he was then in turn Sales Engineer for UPS and sales manager for protection of persons.
Since 1991 he is in charge of prescription for LV Power distribution.



Roland Calvas

An ENSERG 1964 engineering graduate (from the Ecole Nationale Supérieure d'Electronique et Radioélectricité de Grenoble) and an Institut d'Administration des Entreprises graduate, he joined Merlin Gerin in 1966.
During his professional career, he has been sales manager and then marketing manager for protection of persons. He is currently in charge of technical communication for the groupe Schneider.

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glossary

Electrocution	Electro Shock resulting in death
Electro Shock	Application of a voltage between two parts of the body
EMC	Electro Magnetic Compatibility
GFLD	Ground Fault Location Device
$I\Delta n$	Operating threshold of a RCD
MT/HVA	Medium Voltage: 1 to 35 kV as in CENELEC (circular of the 27.07.92)
	Class A High Voltage: 1 to 50 kV as in French decree of the 14.11.88
PIM	Permanent Insulation Monitor
RCD	Residual Current Device
SCPD	Short-Circuit Protection Device (circuit breakers or fuses)
STD	Short Time Delay protection (protection against short-circuit overcurrents by circuit-breaker with rapid trip release)
TBM	Technical Building Management
TEM	Technical Electrical Power Distribution Management
TPM	Technical Process Management (automation of...)
U_L	Conventional limit voltage (maximum acceptable contact voltage) known as the «safety» voltage

earthing systems worldwide an evolutions

summary

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Following an historical review of the origins of **Earthing Systems**, this «Cahier Technique» goes on to provide information on the practices in some countries concerning medium voltage, HV/LV substations, in particular in LV public, industrial and tertiary distribution.

Electrical installations are evolving, electronics are everywhere, thus leading us to look afresh at earthing systems used in LV and indeed even to predict an evolution which should bring the TN-S and TT systems closer together.

The criteria for the selection of earthing systems has changed. We advise those not very familar with earthing systems standardised by IEC 364 to first read «Cahier Technique» n° 172.

1. review of standardised earthing systems

Electrical power was actually used in 1900.

Today electrical installation standards are highly developed and cover all major aspects for a safe installation.

In LV, the reference standard is IEC 364 (see appendix no. 1).

Standard makers have paid particular attention to the measures to be implemented to guarantee protection of personnel and property (part 4 of the above-mentioned standards).

This concern has resulted in the standardisation of three Earthing Systems.

Before reminding readers of these three systems, a concise historical review will certainly be of use.

history

Electrical hazard and protection of persons

- **in the 18th century**, the static electricity produced by friction of certain insulating bodies formed a «scientific» diversion causing experimenters to jump up.... in drawing rooms.
A few dangerous experiments showed the electrical nature of lightning.
And in 1780: by chance an «electrostatic machine» made a frog’s legs move. Galvani observed the contraction of muscles by electricity.
- **in 1880**: in order to transmit electricity over several kilometres, DC voltage left the 100 V range (required for arc lamp operation) and rose to 1,300 V (1882 exhibition in Munich) (see fig. 1), and then to 3,000 V (Grenoble-Vizille link in 1883).
Insulation faults cause leaks and short-circuits.
The 100 V DC voltage can allegedly be touched without risk.
- **in 1886**: the first distribution installation in the USA: 12 A/500 V/AC generator and 16 small transformers supply consumers with 100 V AC for the first time;

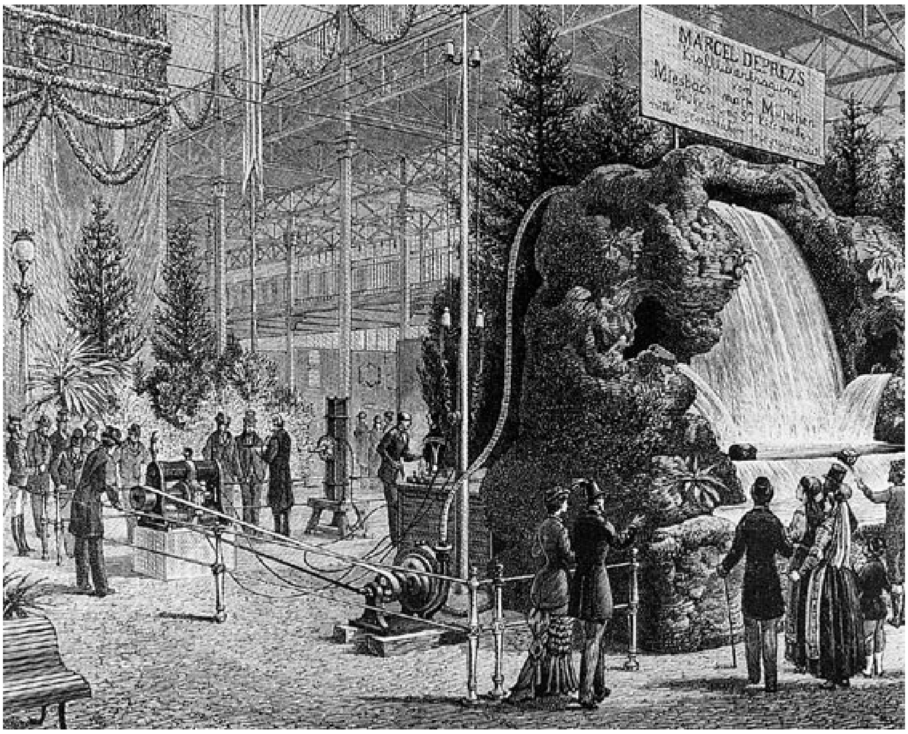


fig. 1: Mr. Desprez's installation located in Munich Palace during the Munich exposition.

- **in 1889**: AC and DC current wage war in North America:
  - ☐ Edison defends DC and describes the dangers of AC for personnel. He carries out tests on dogs and horses,
  - ☐ Westinghouse supports AC.

  Edison challenges Westinghouse to a duel: each will be subjected to identical voltages of 100, 150, 200 V etc. in DC for Edison and in AC for Westinghouse...: prediction: at 200 V AC, death will ensue for Westinghouse!
The duel did not come off... a telegraph operator climbing on a pole was electroducted in the very heart of New York.
- **in 1890**: Kremler entered the electric chair and was electrocuted with... AC current!
Thus, at the end of the 19th century, it was obvious to the technico-scientific community that electric current was dangerous for man, and that AC was more dangerous than DC.

emergence of earthing systems

These systems are the result of a lengthy evolution guided by the search for increased personnel protection.
Between 1880 and 1920, transmission and distribution of electrical power took place in «unearthed neutral».
Lines are uninsulated, placed out of reach, supported by insulators; no points of the network are deliberately earthed.
In homes, voltage is 100/110 V AC.
Throughout this period, fuses blow and persons «receive Electric Shocks»

(see fig. 2). However, in view of distribution voltage level, few persons are electrocuted.

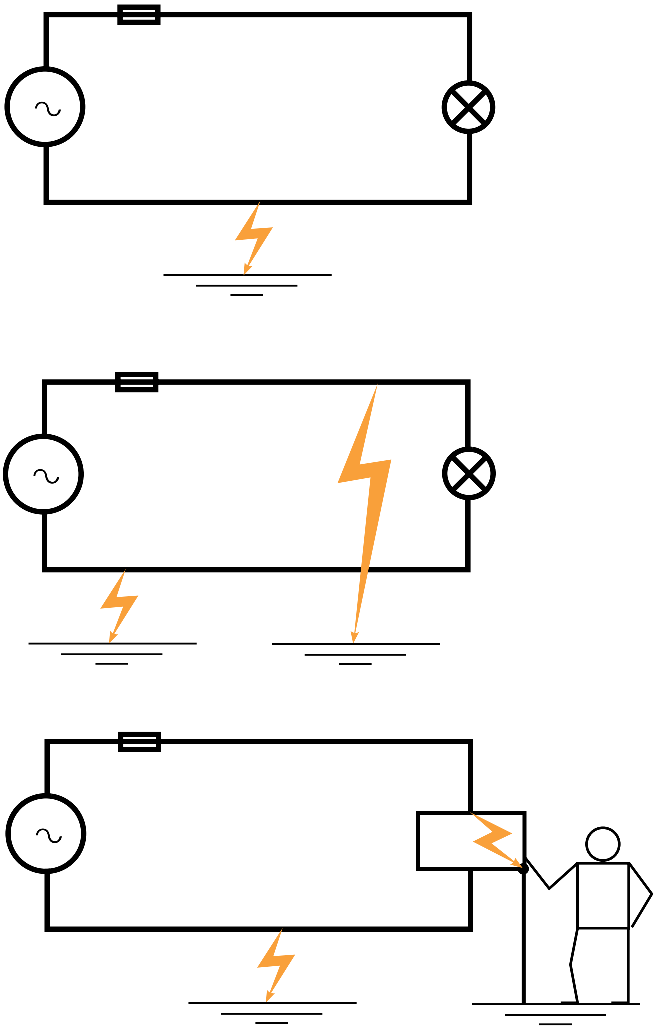
■ in UK, in the last quarter of 19 th century, electric arc lighting was developing rapidly. When it was introduced into houses, insurance companies became concerned about danger of fire due to undersized cables, poor jointing and insulation breakdown. Many insurance companies produced sets of rules to minimise their risks.

In **May 1882**, the Council of the Society of Telegraph Engineers and of Electricians (later to become the Institution of Electrical Engineers), appointed a committee to consider rules for the prevention of fire risks due to electic light. These rules were not popular with the insurance companies who continued to publish their own. The IEE had yet to become a recognised authority on the subject. By the third edition of the IEE rules in 1897, there was still strong opposition from insurance companies and it was not until 1916 that the final opposition crumbled and the IEE rules became universally accepted in the UK.

In the first edition of the rules, in 1882, two items were concerned with danger to people: no one should be exposed to more than 60 V and the potential between two points in the same room should not exceed 200 V. The earthing of metalwork of appliances working at domestic voltages was first required in the eighth edition in 1924, althought it was soon recognised that an adequate earth was not always easy to obtain.

In 1930, the requirement for an earth leakage trip operating at 30 mA or less was introduced (since deleted).

■ in France **in 1923** a «standard» for electrical installations makes earthing of frames a «requirement»:
□ casings of fixed and moving motors, which may be touched in a non-insulated area, in installations with a voltage greater than 150 V,
□ fixed and portable electrical household appliances with a power greater than 4 kW,
□ electrical bath heater enclosures installed in bathrooms,
□ metal parts placed in premises steeped in conductive liquids and which, due to insulation faults, might become live.



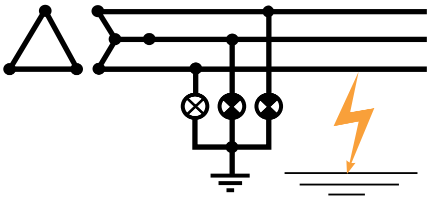
1st fault
nothing happens

double fault
the fuse blows
if full fault

Earthing of load
frames (1923) to prevent
Electric Shock by
«indirect» contacts

fig. 2: the emergence of the unearthed neutral.

The standard provides absolutely no information on earthing conditions or on the value of earth connection resistance, and stipulates no protection device. Although it contains a few rules for fuses these are only for installation conditions.
In order to prevent fuses blowing on a double insulation fault, it quickly become obvious that indication of the presence of the first fault was a good idea.
For this reason, the first failsafe insulation monitor was installed in industrial installations (see fig. 3).



A lamp going out indicates
an insulation fault on
the corresponding phase.

fig. 3: lamp insulation monitor in industry.

If a lamp goes out, there is a fault between the corresponding phase and the earth.
Thus the first earthing system came into existence: the unearthed neutral. The Permanent Insulation Monitor (PIM), with three lamps (in three-phase) was used up to 1955.

In 1951, the first «tube» PIMs, injecting DC, were installed in mines: insulation of phases and neutral was monitored.

In 1962 the first transistor PIMs (Vigilohm TA) were produced, and in 1972 the first PIMs injecting low frequency AC.

In 1927 a decree stipulated the earthing of the transformer neutral in public distribution in France (U ⩾ 150 V AC).

At this time, production of electricity in France was approximately 350 kWh/inhabitant/year (in 1900 it was 7); a tenth of this production was distributed in LV.

Electricity firms supply a number of consumers by transformer. However, in unearthed neutral, two earthing faults occurring at two different consumers, do not always cause fuses to blow and there is a definite risk of «fire» (the «indirect contact» risk exists, but is low and not known).

Application of the 1927 decree thus stipulates more reliable disconnection of the faulty consumer, thereby ensuring a sound network is maintained.

In 1935, the decree on protection of workers and standard C 310, taken up by standard C 11 of 1946, began to mention the risk inherent in insulation faults. It is at this moment that the combination of «earthing of loads and automatic breaking devices» first appeared. The latter may be fuses, «RCDs» or voltmeter relays of frame/earth voltage (see fig. 4).

Note that protection devices with a threshold of under 30 A are supposed to guarantee safety!
The first residual current connection circuit-breakers were manufactured in 1954. In addition to protection of persons and disconnection of consumers, they made it possible to combat illegal connections (current stealing between phase and earth when 127 A single-phase moves to 220 V two-phase) (a single current measuring winding in the meter).

This is how the earthed neutral came into existence in France. However, it was not until the decree of the 14.11.62 on protection of workers and standard C 15-100 (blue) of the 28.11.62 that fault loop impedance and thus earth connections were defined accurately, according to fuse rating or RCD threshold then set by standard C 62-410 at 450 ± 200 mA.
Standard C 15-100 of 1962 thus gave official status to the unearthed neutral and the earthed neutral (measurement B1), as well as to the TN system (measurement B3).
It made a clear distinction between direct and indirect contact and lists the primary protection measurements (A) and how to protect by automatic disconnecting devices (B), without however giving information on operating times.

Alongside the standard, the decree of the 14.11.62 legalised the unearthed and the earthed neutrals.
In 1973 a decision of the Board of Employment authorised the TN system in France.
Between 1962 and 1973 each earthing system had its ardent supporters in France and elsewhere. The TN system has the advantage of a simple principle: the SCPDs de-energise loads (or LV consumers) having an insulation fault.
The TN system (exposed-conductive parts connected to neutral) is used in some countries in public distribution (not in France): (see fig. 5).
As personnel protection against indirect contact is involved, use of this system requires complete mastery of loop

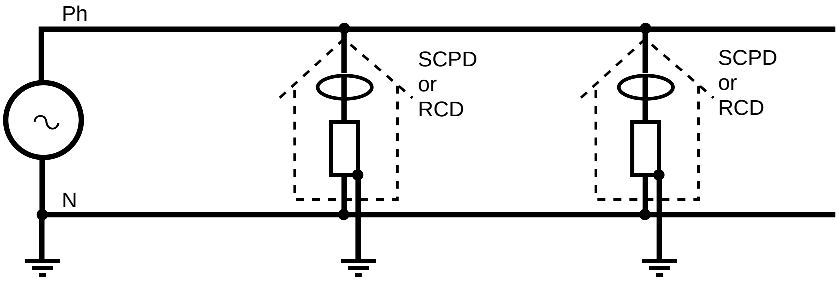


fig. 4: earthing in public distribution.

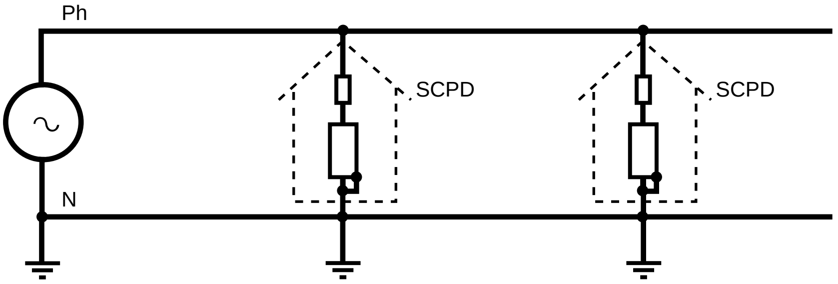


fig. 5: TN-C system in public distribution.

impedances (irrespective of where the fault occurs) to ensure operation of the SCPD which will disconnect the faulty part within the specified time.

Definition of these times by IEC experts in the nineteen seventies, according to impedance of the human body and pathophysiological effects, has made its use possible.

It should be noted that transformation of an insulation fault into a short-circuit increases risk of damage to equipment and of fire. With this in mind, let us remember that protection is based on the rapid evolution of an insulation fault to a full fault between phase and neutral.

earthing systems of IEC 364

The three earthing systems internationally standardised are currently taken over in many national standards.
These three systems have been studied in detail in «Cahier Technique» n° 172 and, for each of them, the hazards and associated protection switchgear have been presented. We shall however briefly review their protection principle.

The TN system
(see fig. 6)

- the transformer neutral is earthed;
- the frames of the electrical loads are connected to the neutral.

The insulation fault turns into a short-circuit and the faulty part is disconnected by Short-Circuit Protection Devices (SCPD).
The fault voltage (deep earth/frame), known as «indirect contact» is ≈ Uo/2 if the impedance of the «outgoing» circuit is equal to that of the «return» one. When it exceeds the conventional limit voltage (U_L), which is normally 50 V, it requires disconnection, which must be especially quick when Ud is larger than U_L.

The TT system
(see fig. 7)

- the transformer neutral is earthed;
- the frames of the electrical loads are also connected to an earth connection.

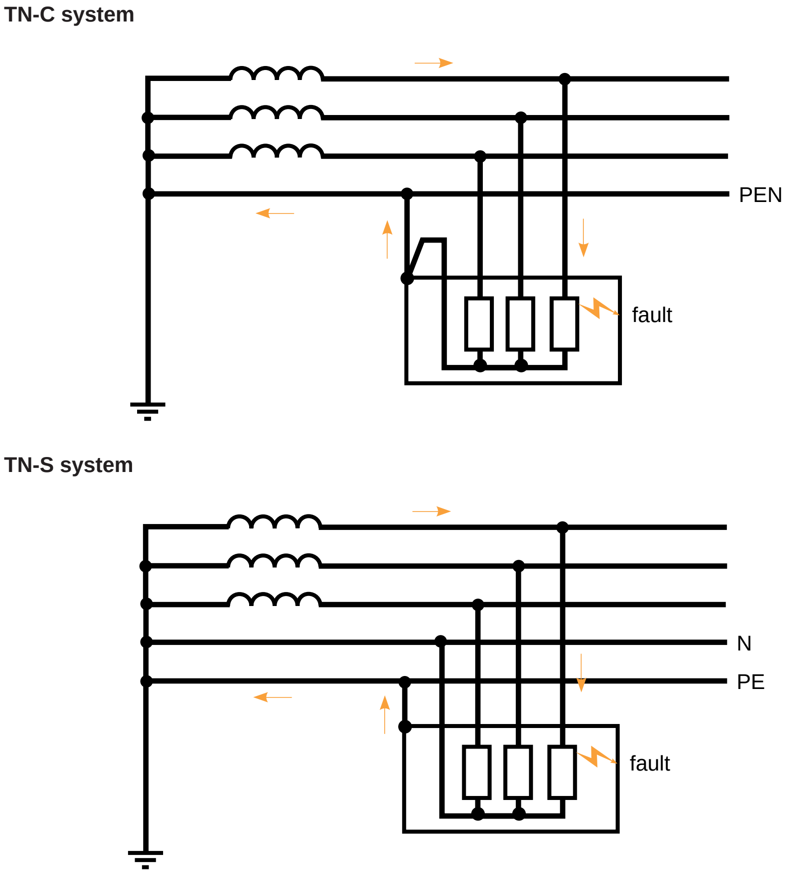


fig. 6: TN-C and TN-S systems.

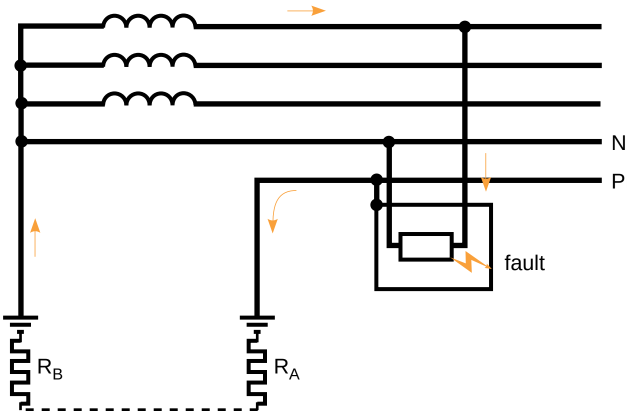


fig. 7: TT-system.

The insulation fault current is limited by the impedance of the earth connections and the faulty part is disconnected by a Residual Current Device (RCD).
The fault voltage is:

$Uc = Uo \dfrac{R_A}{R_B + R_A}$ greater than voltage U_L, the RCD comes into action as soon as $Id \geqslant \dfrac{U_L}{R_A}$.

The IT system

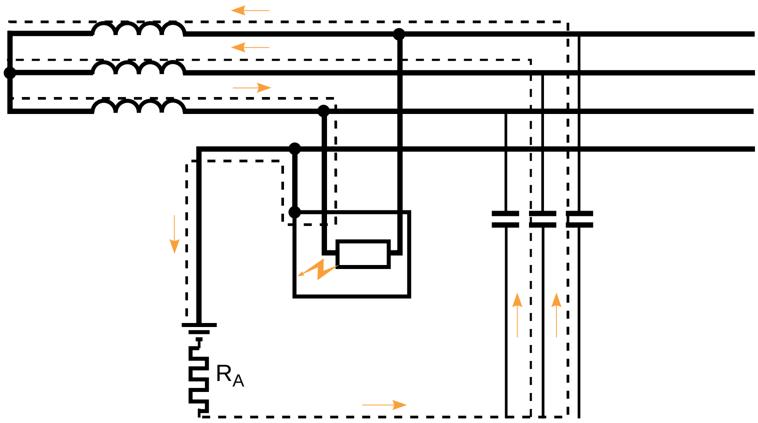
- the transformer neutral is not earthed. It is theoretically unearthed, but in fact is connected to the earth by the stray capacities of the network and/or by a high impedance ≈ 1,500 Ω (impedance-earthed neutral).
- the frames of the electrical loads are connected to the earth. If an insulation fault occurs, a small current is developed due to the network's stray capacities (see first diagram, fig. 8).

The voltage developed in the earth connection of the frames (a few volts at the most) does not present a risk.

If a second fault occurs (see second diagram, fig. 8) and the first one has not yet been eliminated, a short-circuit appears and the SCPDs must provide the necessary protection.

The frames of the relevant loads are brought to the potential developed by the fault current in their protective conductor (PE).

1^{st} fault



double insulation fault

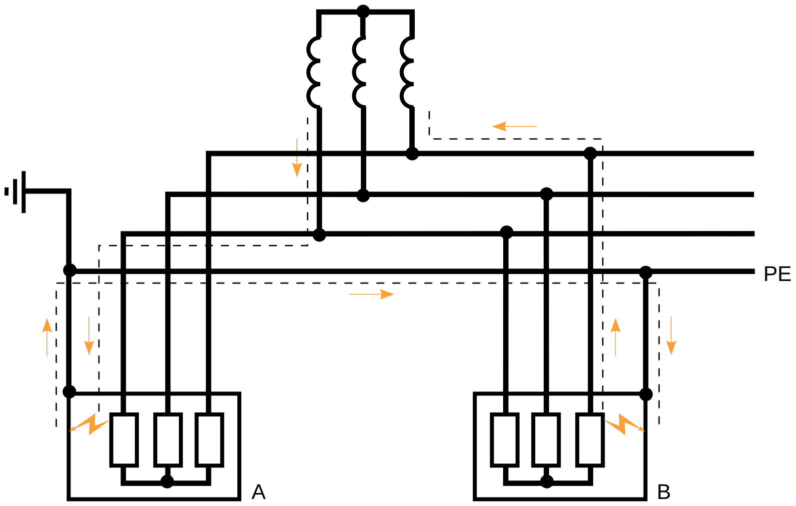


fig. 8: IT system.

2. earthing systems worldwide

general

In all industrialised countries, LV networks and loads are earthed for safety reasons to guarantee protection against electric current for persons.

The objectives are always the same:

- fixing the potential of live conductors with respect to the earth in normal operation;
- limiting voltage between the frames of electrical equipment and the earth should an insulation fault occur;
- implementing protection devices which remove the risk of Electric Shocks or electrocution of personne;
- limiting rises in potential due to MV faults.

influence of MV earthing systems

While the first three objectives listed above fall into the range of LV earthing systems, the fourth has considerable repercussions on safety of personnel and property in LV. Thus, at MV/LV substation level, a MV phase/frame fault or a fault between MV and LV windings may present a risk for equipment and users of the LV network.

In public and industrial MV, except in certain special cases, the neutral is not distributed and there is no protective conductor (PE) between substations or between the MV load and substation. A phase/earth fault thus results in a single-phase short-circuit current limited by earth connection resistance and the presence of limitation impedances, if any (zero sequence generator).

The current tendency, in various countries, is to limit the zero sequence fault currents of MV networks, thus allowing:

- increased continuity of service (availability of electrical power) by authorising automatic reconnection on a transient fault,
- connection or not of the frames of the MV/LV substation and those of the LV neutral to avoid risk for LV users and equipment.

IEC 364-4-442 states that the earthing system in a MV/LV substation must be such that the LV installation is not subjected to an earthing voltage of:

- Uo + 250 V: more than 5 s;
- Uo + 1,200 V: less than 5 s

(Uo $\sqrt{3}$ in IT). This means that the various devices connected to the LV network must be able to withstand this constraint (see fig. 9a).

The same standard states that if Rp > 1 Ω, the voltage Rp Ih_{MT} must be eliminated, for example:

- in under 500 ms for 100 V;
- in under 100 ms for 500 V.

If this is not so, Rp and R_N must be separate whatever the LV earthing system. This rule, not always complied with in certain countries, often leads to the separation of the two earth connections (for MV networks with a high zero sequence fault current). If all the earth connections (substation-neutral-applications) have been grouped into a single one, a rise in potential of LV frames may be observed which can be dangerous (see fig. 9b).

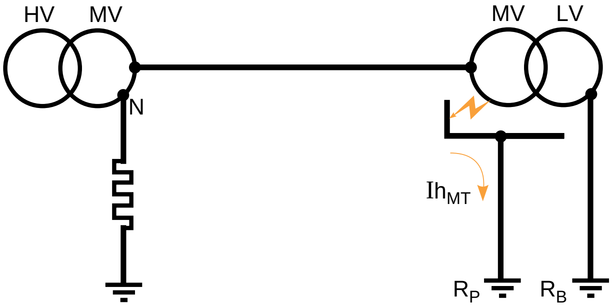


fig. 9a: if Rp and R_B are connected, the fault current causes the potential of the LV network to rise with respect to the earth.

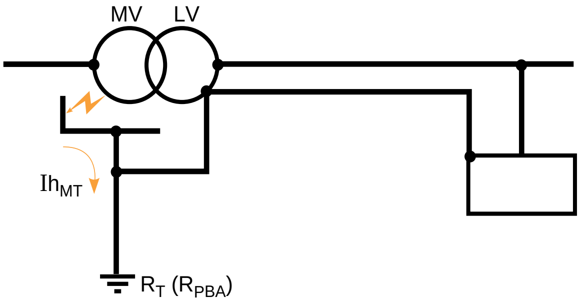


fig. 9b: the LV load frames are raised to the potential $Ih_{MT}\,R_T$.

The table in figure 10 gives a few examples for public distribution worldwide. It shows that, in many countries, the earth connections of the substation and neutral must be separate if their resulting value is not less than 1 Ω.
Note that the impedance-earthed IT earthing system is the most commonly used in MV industrial networks. The «zero sequence generator» supplies a resistive current around twice the capacitive current of the network (see «Cahier Technique» n° 62), thus allowing use of a RCD to ensure protection by disconnection of the faulty feeder.

LV earthing systems

The MV/LV transformers used are generally Dy 11 (delta/star). However the use of midpoint single-phase distribution for public distribution in the USA and Japan should be pointed out (see fig. 11).
Most countries apply or derive inspiration from standard IEC 364 which defines the TN, IT and TT earthing systems and the protection conditions, both for public and private distribution.

In public distribution

The most common systems are TT and TN; a few countries, in particular Norway, use the IT system.
The table in figure 12 lists some examples for public distribution (LV consumers).
This table shows that Anglo-Saxon countries mainly use the TN-C, whereas the TT is used in the rest of the world.

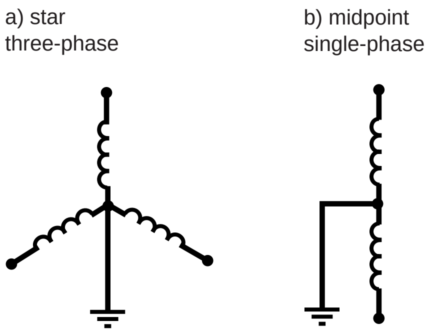


fig. 11: coupling of the secondary windings of MV/LV transformers.

country	MV earthing system	frame connection	observations
Germany 10 and 20 kV	unearthed or compensed Id < 60 A	connected if Id x R_T < 250 V	Rp < 2 Ω or 5 Ω
Australia 11 and 12 kV	directly earthed Id= a few kA	separated except if R_T < 1 Ω	Rp < 10 Ω
Belgium 6.3 and 11 kV	limitation impedance Id < 500 A	separated d ⩾ 15 m	Rp < 5 Ω
France 20 kV	limitation impedance	separated except if R_T	
overhead	Id ⩽ 300 A	< 3 Ω	Rp < 30 Ω
underground	Id ⩽ 1,000 A	< 1 Ω	Rp < 1 Ω
Great Britain 11 kV	direct or limitation impedance Id < 1,000 A	separated except if R_T < 1 Ω	Rp < 25 Ω
Italy 10-15 and 20 kV	unearthed Id ⩽ 60 A (more in reality)	separated	Rp < 20 Ω
Ireland 10 and 38 kV	unearthed on 10 kV compensated on 38 kV Id < 10 A	separated except if R_T < 10 Ω	stipulations on how to produce Rp
Japan 6.6 kV	unearthed Id < 20 A	connected R_T < 65 Ω	
Portugal 10 to 30 kV	limitation impedance	separated except if R_T < 1 Ω	Rp < 20 Ω
overhead	Id ⩽ 300 A		
underground	Id ⩽ 1,000 A		
USA 4 to 25 kV	directly earthed or by low impedance Id = a few kA	connected	the earths of the source of the MV/LV substation and of the LV neutral are connected

fig. 10: public distribution examples - MV earthing systems.

country	LV earthing system	observations
Germany 230/400 V	TT and TN-C	the TN is the most commonly used; R_T must be < 2 Ω; earth connection at the consumer's, even in TN
Belgium 230/400 V	TT	Ru < 100 Ω 30 mA RCD for sockets
Spain 230/400 V	TT	Ru < 800 Ω with 30 mA RCD at supply end of the installation
France 230/400 V	TT	Ru < 50 Ω, (100 Ω shortly) 30 mA RCD for sockets
Great Britain 240/415 V	TT and TN-C	- town areas: TN-S and TN-C (New Est installations: 15 %), the earth connection (< 10 Ω) of the neutral is provided by the distributor - rural areas: TT
Italy 230/400 V	TT	RCD with IΔn as a function of Ru (IΔn < 50/Ru). For consumers without earth connection 30 mA RCD
Japan 100/200 V	TT	Ru < 100 Ω, frequent use of 30 mA RCD, no search for equipotentiality
Norway 230/400 V	IT	premises in insulating materials and poor earth connections account for this choice. homes with signalling 30 mA RCD. tripping of connection circuit breaker if 2 faults.
Portugal	TT	Ru < 50 Ω (100 Ω as from 1995).
USA 120/240	TN-C	earthing of neutral at LV consumers (all earth connections are connected to the source substation).

fig. 12: public distribution examples worldwide (LV consumers) - LV earthing systems.

The TN-C requires costly equipotentiality research:

- for the distributor:
  - in the USA, installation of an additional conductor throughout MV and LV distribution with earthing every 400 m,
  - in Great Britain, numerous earth connections are installed on the town public LV network neutral, if TN-C used, thus meaning consumers may not need their own earth connections,
  - in Germany, an earth connection is made for the neutral just upstream from the consumer's connection point,
- for the consumer:
  as a rule, connection to the protection conductor of the metal structures of the building and all the metal ducts.

In industrial and tertiary LV distribution

The 3 earthing systems are used to various degrees in all countries:

- the TN-C system is particularly used in Anglo-Saxon countries for carefully designed and produced installations (SCPD/loop impedance matching) corresponding to modern blocks of flats where all metal parts are connected to the protective conductor and where explosion and fire risks are extremely low.
  It is not currently recommended in premises equipped with communicating electronic systems (computer TBM, TPM and CTM -Centralised Technical Management- networks) as currents in the neutral and thus in the PE cause potential references to vary. Do not forget that the TN-C can no longer be used when cross-section of live conductors is < 10 mm^2 Cu.
- the TN-C system is also used in Anglo-Saxon countries and requires an additional conductor and careful design and production. However its use is more flexible and RCDs are used for personnel protection (for very long cables), for fire protection and for extensions without loop impedance calculation.
  Nonetheless, the insulation fault currents which are short-circuit currents, may, if the PE is connected, in distribution, to metal structures, generate electromagnetic disturbances preventing electronic equipment from working properly (sum of currents in cable not zero and «stray» currents).

Finally, as the neutral is not protected in some countries (measure authorised by standard IEC 364), it may be damaged by overcurrents, in particular when loads generating rank 3 harmonic currents and multiples are supplied by the network. In some cases this results in neutral cross-section being doubled (seen in the USA).... In the long term, international standards should specify systematic protection of the neutral and indeed protection (without breaking) of the PEN in TN-C.

- the IT system requires as much care as the TN-S one. Permanent insulation monitoring allows fault prediction, currently simplifed by digital systems which monitor insulation evolution for each feeder.
  This system calls for fault tracking and elimination; thus electrical engineers should preferably be present on site.
  In many countries, the unearthed neutral is used whenever continuity of service is essential or when human life is at stake (e.g. hospitals), however, in UK, TN-S is used in hospitals.
- the TT system is the easiest one to implement; insulation fault currents are 1,000 times smaller than in TN or IT (2nd fault), thus accounting for its value as regards risk of fire, explosion, material damage and electromagnetic disturbances.
  Its weak point is the risk of disruptive breakdown by return on an insulation fault in the substation on the MV side if the zero sequence fault current is high and if the substation and neutral frames are connected.

There are no statistics on use of earthing systems worldwide, but the TT system is by far the most commonly used.
Moreover, its simplicity makes it without doubt the system best suited to developing countries.
Following these brief considerations on the three official earthing systems, we shall now see how they are implemented in some countries.

earthing systems of private LV networks in some countries

In the USA

All the various earthing systems are used: the TN-S (see fig. 13) is the most common, but the IT and impedance-earthed IT are used in process factories.

- implementation of the TN-S has two major special features:
  - the neutral is not protected and not switched, which may present risks for persons and property:
    - potential of the neutral compared with the earth may be high on a fault originating at MV level; this presents a risk
    - rank 3 harmonic currents and multiples of 3 add up in the neutral and may cause unacceptable temperature rise
  - the protective conductor is often made up by the cable path and the metal tubes conveying the live conductors:
    - the impedance of this PE is hard to control. Thus NEC paragraph 230-95 (National Electrical Code) considers that SCPDs do not always guarantee safety in the event of an insulation fault,

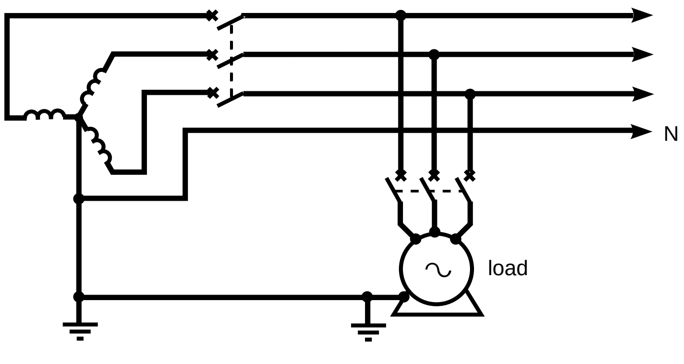


fig. 13: TN-S earthing system in the USA.

- as the PE is not mechanically connected to the faulty live conductor (cables on cable path acting as a PE), the electrodynamic forces due to the high fault current separate the cable from its support (American LV networks have very high prospective fault currents). This causes a transient fault with, as a result, a risk of non-operation of the SCPDs and an increase in fire risk.

Note that when the PE is a distributed conductor, earthing of the transformer neutral is sometimes performed through a low impedance, in order to limit the I^2t at the fault point (Id ⩽ than 1,000 A).

■ protection devices used in TN-S

In addition to the use of SCPDs, remember that to the American way of thinking the main purpose of the «earth» protection devices used is protection of property and limitation of the fire risk.

In this field, the NEC imposes minimum requirements, i.e. use of residual current protection devices on LV installations when the following 3 conditions are met:

- neutral directly earthed,
- phase-to-neutral voltage greater than 150 V and less than 600 V,
- nominal current strength of the device at the supply end greater than 1,000 V,

☐ implementing the RCDs

This protection can be performed in three ways:

- «Residual Sensing» (detection of residual current by vectorial addition of currents in live conductors), (see fig.14). This assembly, known as Nicholson's, requires the installation of a current transformer on the neutral; in the USA the neutral is neither switched nor protected.
- «Source Ground Return» (residual current device placed in the neutral-earth link) and usable only at the supply end of the installation. It allows parallel-connection of sources (see fig. 15),
- «Zero sequence» (classical RCD). For low current detection, it can be used at various levels of the installation to form discriminating protection (see fig. 16),

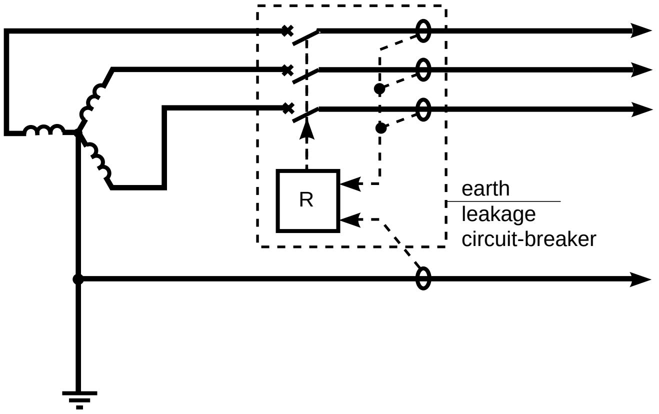


fig. 14: residual sensing.

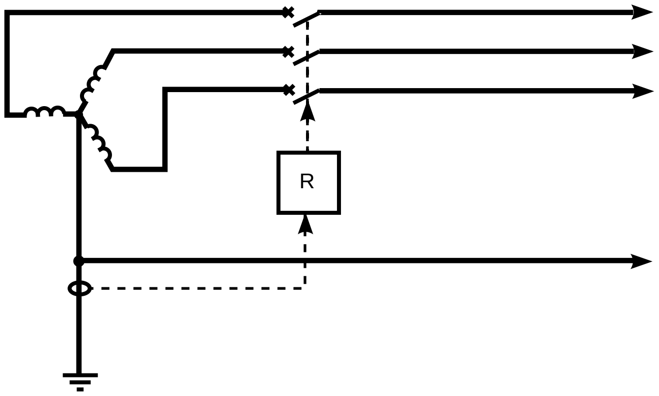


fig. 15: source ground return.

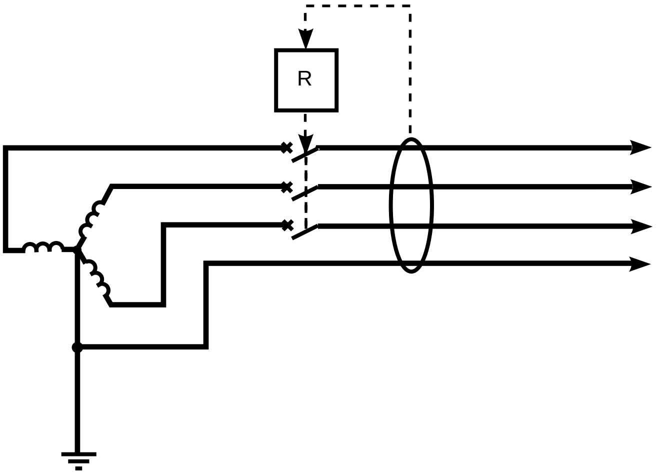


fig. 16: zero sequence.

□ incoming device settings:
- max threshold: 1,200 A,
- tripping time: must not exceed 1 s for a fault current of 3,000 A.

Note

The NEC does not specify a tripping time at 1,200 A, but it is common practice to install protection devices with lower thresholds and as instantaneous as possible.

■ discrimination of residual current devices.

The NEC 230 paragraph 95 only stipulates earth protection for the incoming device. Naturally, this protection must also be installed downstream to prevent the entire installation being put out of operation in the event of one earth fault.

Discrimination has then also to be achieved between the various protection devices. This problem can be solved in two ways:

□ between the earth protection devices with discrimination of the:
- time type by a time delay of 0 s to 1 s,
- logic type or «Zone Selective Interlocking»; recommended in the USA, it prevents long time delays (reduction of the passing I^2t) and easily achieves discrimination on 3 levels or more,

□ between the earth and thermal-magnetic protection

Discrimination will be determined by comparing the setting threshold of the upstream earth protection with the curve $I = f(t)$ of the thermal-magnetic setting of the downstream protection device (see fig. 17).

Use of fewer «earth» protection devices in subdistribution switchboards leads to higher settings of protection devices, resulting in increased risk of damage.

In the Republic of South Africa

In the RSA, industrial and tertiary electrical installations comply with IEC standards.

All three earthing systems are used, with a preference for the TN-S.

A country with a long mining tradition, the RSA uses in its gold mines, for

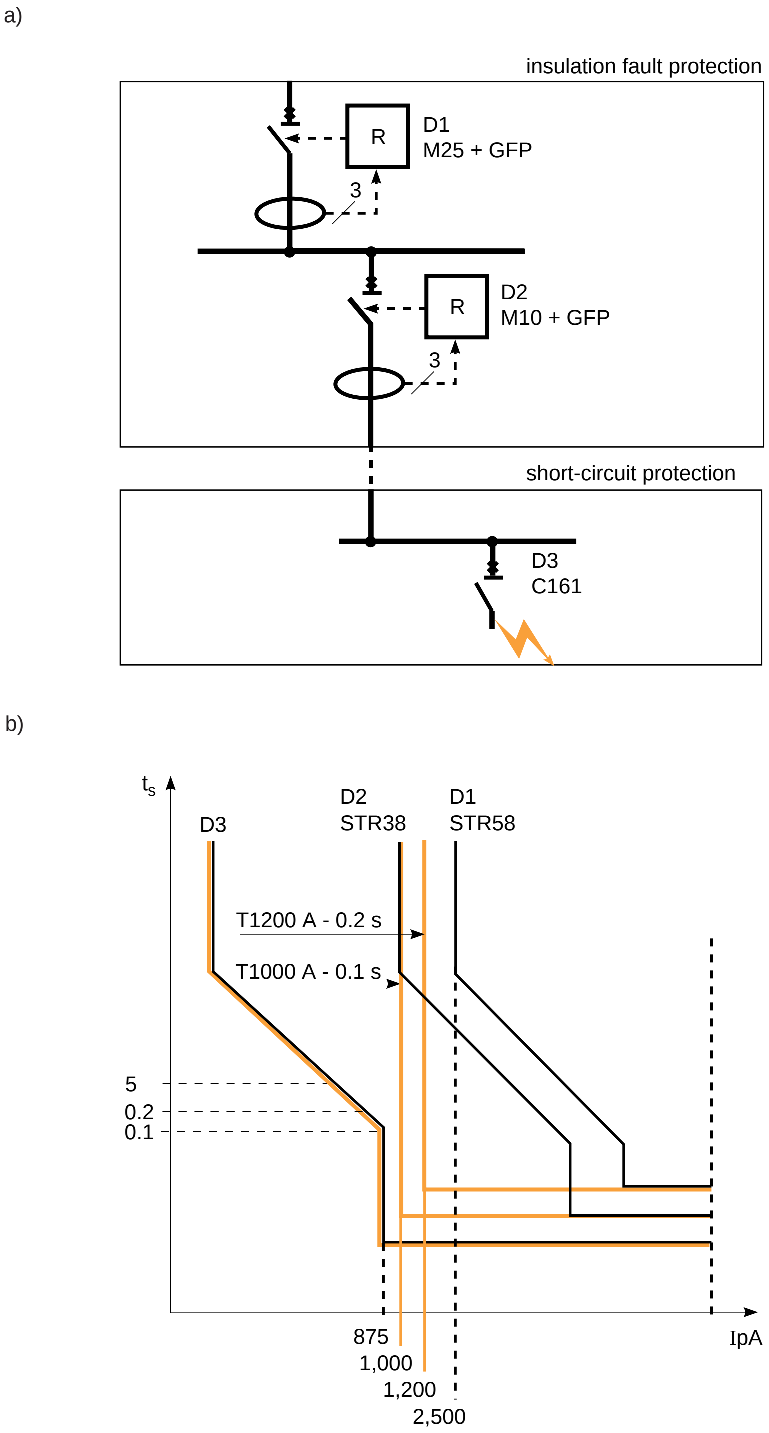


fig. 17: discrimination between downstream short-circuit protection (D3) and upstream earth protection (GFP) (orange).

example, an earthing system which is half TN-S and half TT (see fig. 18).
It uses RCDs for protection.

Characteristics of this earthing system:
- the protective conductor is distributed;
- the load frames are connected to the PE which is earthed at MV/LV substation level;
- a resistor placed between the transformer neutral and the earth connection limits the insulation fault current to less than 20 A.

This system has both advantages and drawbacks:
- advantages:
  - a low contact voltage despite use of a network voltage of 525/900 V,

$$\frac{U_o\ R_{PE}}{R_{PE} + R_{Ph} + 27\,\Omega}$$

  - a low fault current, thus considerably reducing risk of fire and damage to faulty loads,
  - discriminating protection by RCD with use of time discrimination.

Note that use of RCD is particularly advantageous since the LV network topology is constantly evolving (loop impedance!).
- drawbacks:

In the event of HV/LV disruptive breakdown in the transformer, there is a risk of rise in potential of the live LV network conductors compared with the earth and frames (Ih_{MT} R): this risk can be reduced by use of a surge limiter.
Moreover, a residual current device placed on the neutral/earth circuit causes the MV circuit-breaker to open immediately if it detects a fault current greater than 20 A.
- additional measure

Limitation resistance is monitored by an ohmic relay:
  - if resistance is broken: the earthing system becomes an IT: operation can continue, but the RCD will open a feeder on a double fault,
  - if resistance is short-circuited, the earthing system becomes TN-S and the first insulation fault causes the BT circuit-breaker to open, unless, of course, the electrical maintenance service has acted in time.

Compared with the classical TT and TN-S systems, this earthing system is to be preferred when Uo voltage is greater than 400 V (as is the case in mines), since it limits contact voltage.

The desire to limit insulation fault currents is fairly widespread for a variety of reasons:
- high short-circuit power: USA;
- uncertain loop impedance: mines, worksites;
- limitation of damage and/or fire hazard: process - mines - petrochemistry (note that British Petroleum (BP) produces all its installations worldwide using the impedance-earthed TN-S (see fig. 18) with a resistance of 3 Ω in LV and of 30 Ω in 3.2 kV).

In China

China is waking up! However, it has long been under the technical influence of the USSR, which is a member of the IEC (Russian is one of the IEC's official languages together with English and French).
Consequently, all three earthing systems are known and are used to varying degrees.
- IT is used when continuity of service is vital and there is a real risk for persons (hospitals);
- TT used in public distribution, is also used in industry and the tertiary sector, but increasingly less so, perhaps due to the rare use of time discrimination;
- TN-C, which originated in the USSR, has completely gone out of use;
- TN-S is increasingly chosen by Design Institutes for large projects.

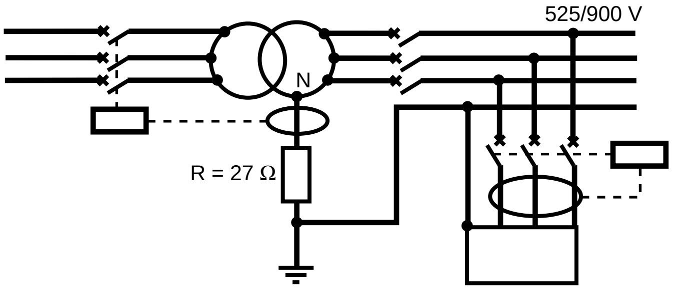


fig. 18: earthing system used in RSA (mines).

3. evolutions and choices of earthing systems

evolution of electrical installations

In **1960** the tertiary sector had barely started to develop: plants, normally large in size, were often installed next to source substations.
The main concern of companies was operation of processes; boasting a competent electrical service, some of them would be won over by the unearthed neutral.
Little by little, the safety guaranteed by this system led it to be stipulated in tertiary installations where dependability was of prime importance: e.g. hospitals.

In the **1990's**, electrical power is the universal driving force in homes, tertiary and industry.
Although public distribution has made enormous headway in terms of availability of electrical power, this availability is still not always sufficient, and generator sets and uninterruptible power supplies are thus used.

- the housing sector no longer accepts power cuts;
- tertiary is a major computer consumer;
- industry has set up in rural areas, is a major automation system consumer and is increasingly using static converters; for example, motors are controlled by a speed controller and functionally linked to a PLC.

In all buildings, «intelligent» devices are increasingly being controlled by technical management systems (process - electrical distribution - building utilities).
These digital systems, including distributed computing, nowadays require the problem-free joint existence of high and low currents; in other words, electromagnetic compatibility (EMC) is vital.

A clash of technical cultures is inevitable:

- electrical engineers have problems with the harmonics generated by static converters. These harmonics cause temperature rises in transformers, destruction of capacitors and abnormal currents in the neutral;
- electronic engineers place filters upstream of their products, which do not always withstand overvoltages and lower network insulation;
- lamp manufacturers are unaware of the problems caused by energising inrush currents, harmonics and high frequencies generated by certain electronic ballasts;
- computer engineers (same applies to designers of distributed intelligence systems) are concerned with equipotentiality of frames and conducted and radiated interference.

These specialists sometimes have problems understanding one another and do not necessarily all have the same approach. Also, very few of them are familiar with earthing systems and their advantages and drawbacks faced with the evolution in the techniques described above.

earthing systems and disturbances in electronic systems

Electromagnetic disturbances assume many different forms, namely:

- continuous or occasional;
- high or low frequency;
- conducted or radiated;
- common or differential mode;
- internal or external to the LV network.

Choice of earthing system is not a neutral one as regards:

- sensitivity to disturbances;
- generation of disturbances;
- effects on low current systems.

Readers wishing to improve their knowledge in this area should study the following «Cahiers Techniques»:

- n° 149 - EMC: Electromagnetic compatibility;
- n° 141 - Les perturbations électriques en BT;
- n° 177 - Perturbations des systèmes électroniques et schémas des liaisons à la terre.

This section will only review the most important aspects, without describing earthing system behaviour faced with MV (50 Hz) faults.

Faced with harmonics

The TN-C should be avoided since rank 3 harmonics and multiples of 3 flow in the PEN (added to neutral current) and prevent the latter from being used as a potential reference for communicating electronic systems (distributed intelligence systems). Moreover, if the PEN is connected to metal structures, both these and the electric cables become sources of electromagnetic disturbance.

Note

The TNC-S (TN-S downstream from a TN-C should also be avoided even though risks are smaller).

Faced with fault currents

- short-circuits: avoid separating the live conductors; otherwise the Icc creates an electromagnetic pulse in the resulting loop;
- electrical earthing fault: the PE must follow the live conductors as closely as possible, or, better still, be in the same multi-conductor cable. Otherwise, as above, the transmitting loop effect appears. The higher the fault current, the greater this effect. The TT earthing system will thus be preferred, as the TN and IT (2nd fault) can develop currents a 1,000 times greater.

In TN and IT, do not connect the PE to the metal frames of the building as the return currents may take a variety of paths and turn into transmitting antennae. The same also applies to the power cable, incorporating the PE, in which the sum of currents is no longer zero.

With respect to equipotentiality of frames, the TN and IT (on the 2^{nd} fault) are equivalent since frame potential at the fault point suddenly rises to ≈ Uo/2 whereas it remains at 0 V at the origin of the installation.

This leads to certain specialists specifying in TN and IT the creation of a low current frame circuit separated from the earth circuit (PE), both being connected to the earth connection at the origin of the LV installation.

The TT with distributed PE throughout the installation is the best system in this respect (small Id and same potential reference for all the communicating devices), (see fig. 19).

Faced with lightning and operating overvoltages

These overvoltages, of common or differential mode and with a frequency of 1 kHz to 1 MHz can damage certain electronic devices if they are not fitted with an isolating transformer with a small primary/secondary capacitive coupling.

As regards differential mode overvoltages, all the earthing systems are equivalent. The solution consists in:

- implementing surge reducing at disturbance source level (e.g. RC on contactor coil);
- protecting sensitive equipment by installing a surge limiter (varistor, ZnO lightning arrester) directly at their terminals.

As regards common mode overvoltages (lightning), ZnO lightning arresters should be installed at the origin of the LV installation with the shortest possible earth connections. In this case, although the TN and TT earthing systems may seem more suitable than IT but overvoltages are transmitted on LV phases. In actual fact, at the frequencies considered, the phase/neutral impedance of the LV windings is very high (the phases are as though they were «unearthed» even if the neutral is earthed).

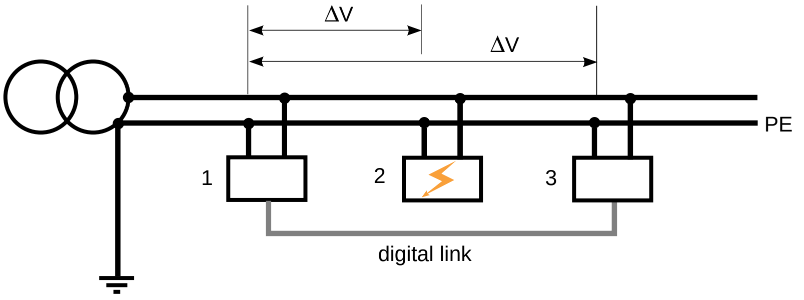
Faced with HF disturbances:

All the earthing systems are equivalent. Advice for minimising the effects of HF disturbances:

- use the Faraday cage effect for buildings (metal structures and meshed floors), or for certain rooms in the building reserved for sensitive equipment,
- separate the frame network (structural and functional frames) from the earth network (PE),
- avoid loops which may be formed by the high and low current circuits of communicating devices or place low current links (frame surfaces - ducts/metal screens - accompanying frames) under a «reduction effect»,
- avoid running them too close to power cables and make them cross at 90°;
- use twisted cables, or, even better, shielded twisted cables.

There are still not many standards in this area and they are often prepared (EMC standards) by electronic engineers. Installation standard IEC 364, sections 444 and 548, should provide increasingly more recommendations.

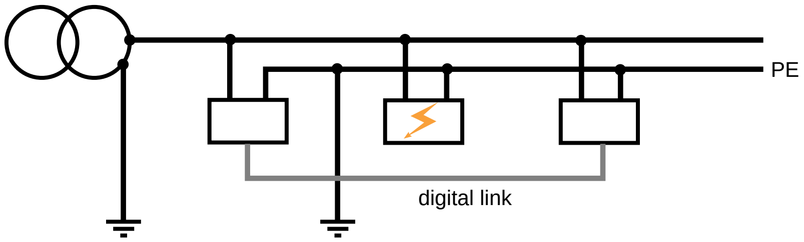
a)



In TN: on an insulation fault, the voltage drop in the PE causes the reference potential of the communicating devices to vary.

The frames of devices 2, 3..., are at the potential $\approx \frac{Uo}{2}$ where as the devices close to the source are at the earth potential.

b)



With a single load frame earth connection:
In TT: all the frames are at the same potential, even during a fault; no disturbance of communictions by bus.

fig. 19: equipotentiality of the PE on an insulation fault.

evolution of earthing systems

Evolution of the TN

The original aim of this earthing system was simplicity, efficiency and minimum installation cost (see the American TN where the neutral is not even protected);

Safety of personnel is guaranteed, but that of property (fire, damage to electrical equipment) is less so.

Proliferation of low current power electronics is increasing and will continue to increase complexity of its implementation.

Derived from the TT of the nineteen twenties, the TN was a solution for controlling fault current value and ensuring that all insulation faults could be eliminated by a SCPD.

It grew up in Ango-Saxon countries where rigour of installation designers and users is excellent.

The logical evolution is TN-C → TN-C-S → TN-S → TN-S with fault current limitation to limit fire hazards, damage to loads and malfunctionings due to widespread use of distributed electronics (see fig. 20).

A survey carried out in Germany in 1990 showed that 28 % of electrical (electronic) problems were due to EMC.

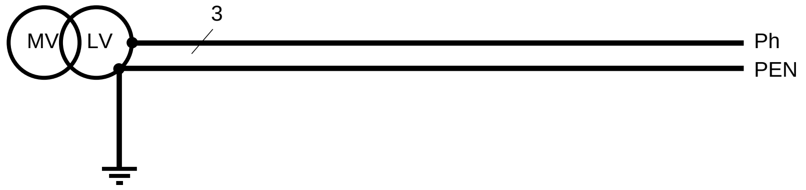
In terms of protection, the TN system often uses fuses; already hindered by an overlong breaking time when limit safety voltage U_L is 25 V, they will be further hindered in the long term if LV networks with voltages greater than 230/400 V are developed. The use of RCDs (impedance-earthed TN-S) solves this problem.

Evolution of the IT

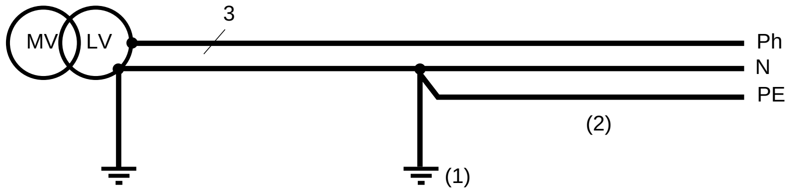
The earliest electrical installations (1920) were produced in IT. However, double faults quickly gave this system a bad name (failure to master loop impedances).

Standards gave it official status in the sixties in order to meet continuity of service requirements of process industries and safety requirements in mines.

a) TN-C earthing system



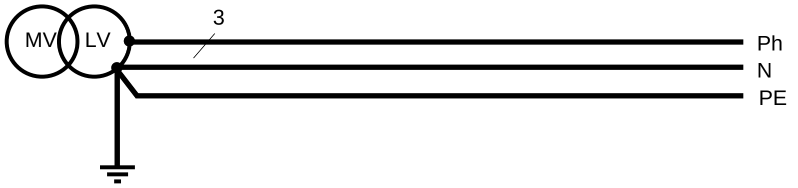
b) TN-C-S earthing system



(1) new earth connection preferable if the transformer is at a distance (public distribution); improves local equipotentiality compared with the eath. This solution is used in Germany and is being experimented in France (in DP).

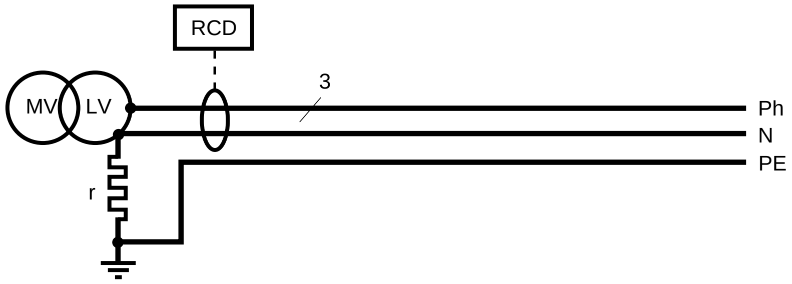
(2) in France, the C 15-100 stipulates changing to TN-S when cross-section of conductors is $\leqslant 10\ \text{mm}^2$ Cu.

c) TN-S earthing system



Avoids equipotentiality disturbances due to flow of neutral current and 3K harmonics in the PEN.

d) impedance-earthed TN-S



Solution used in the USA (Id of the order of 500 A), in RSA ($I\Delta \approx 20$ A); limits fire risks, damage and potential reference problems for distributed electronics.

This earthing system is similar to the TT one.

fig. 20: evolution of the TN.

Today, the IT system closely resembles the TN-S as regards installation (an additional surge limiter and insulation monitor).

It is the champion of continuity of service and safety on the first fault, if this fault is promptly tracked and eliminated.

Following widespread use of the distributed PE throughout the installation (as in TN), this system, in which the second fault current cannot be limited, will not really evolve, except for the rapid fault tracking techniques.

As the likelihood of a double fault increases with the number of feeders and size of the installation, its use should be reserved for parts of the network and for control and monitoring circuits with, naturally, use of isolating transformers (see fig. 21).

On these small circuits, use of the impedance-earthed IT allows signalling RCDs for fault tracking.

Evolution of the TT

To begin with, electrical distribution in France was in single-phase 110 V, followed by two-phase 220 V.

Earthing of frames, combined with use of RCDs, aimed at de-energising consumers with insulation faults and cheaters. The development of electric household appliances led to protect people against indirect contacts.

Protection against indirect contacts by RCD with standardised operating times was made official in the nineteen sixties.

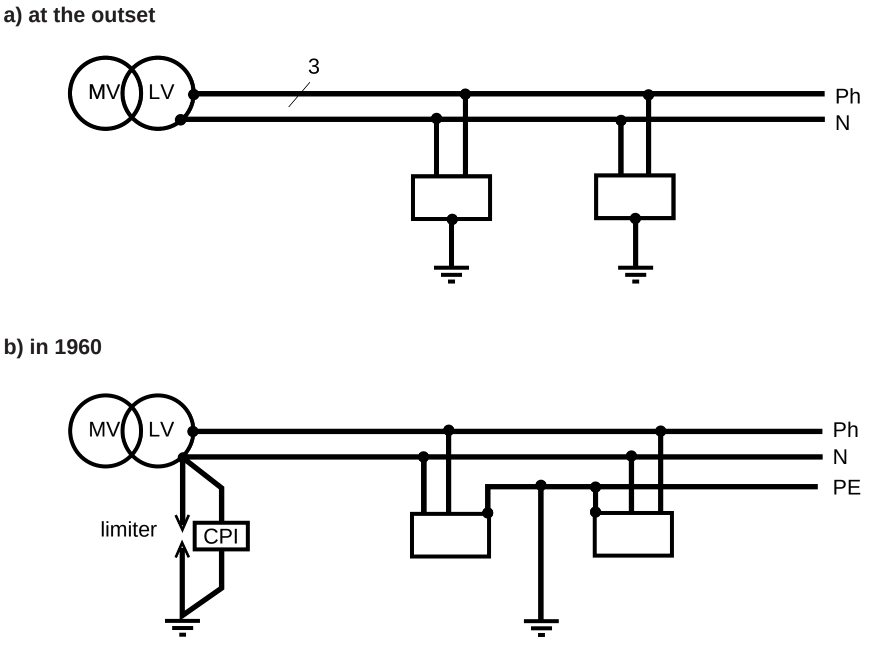
Today, the tendency is (as in TN and IT) to distribute the PE throughout the installation and thus to use only one application earth connection (see fig. 22).

This tendency should continue with the use of the LV neutral earth connection only (as in TN and IT), but maintaining the advantage (damage, fire, EMC) of a small insulation fault current.

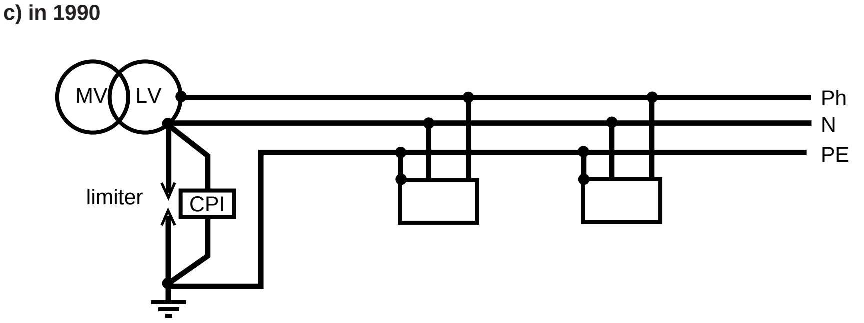
choosing the earthing system

Choice may be determined by normal practice in the country.

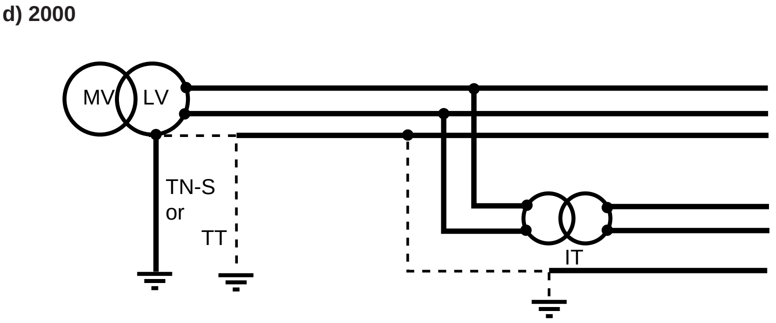
Choice of earthing system should be influenced by electrical power users and network operators (electrical service). Experience shows however that the choice is mainly made by the engineering firms designing the installation.



Limitation of number of earth connections and interconnection of frames or use of RCD to master the double fault.



Becoming more similar to the TN-S (PE distributed, calculation of loop impedances).



IT is used mainly on small networks or parts of networks downstream from TN and TT systems.

fig. 21: evolution of the IT.

For users and operators

These both demand absolute DEPENDABILITY; electrical power should thus always be available and be completely risk-free, i.e. «out of sight, out of mind».

The elements making up installation dependability:
- safety;
- availability;
- reliability;
- maintenability, must therefore be optimised.

In addition, a new requirement, electricity must not disturb the numerous low current devices.

These are the criteria used to make the best choice according to:
- type of building;
- the activity it houses;
- whether or not an electrical service is available.

In safety terms, the TT is the best,

In availability terms, the IT is the most suitable,

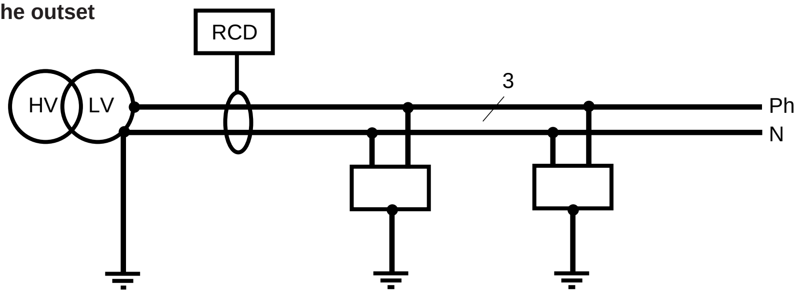
In maintenability terms, fault tracking is fast in TN (thanks to the SCPD) but repair time is often long. Conversely, in IT, tracking of the first fault may be more difficult, but repairs are quicker and less costly.

The TT is a good compromise.

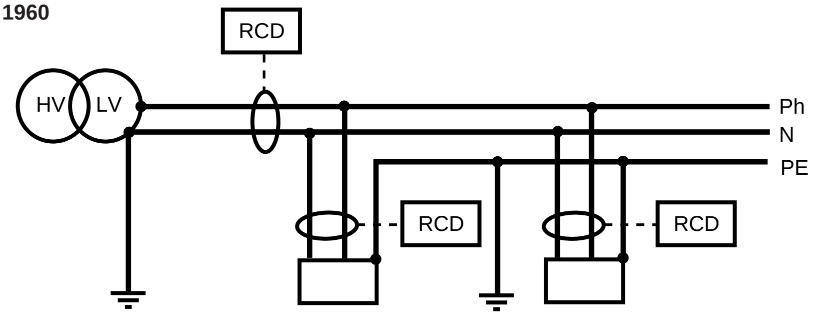
In reliability terms, the protection devices used are reliable, but reliability of the installation and loads may be affected:
- in TN-C by the fact that the PEN, not protected, may be damaged by harmonic currents;
- in TN-C and TN-S;
  - ☐ by insufficient rigour for extensions,
  - ☐ by use of replacement sources with low short-circuit power,
  - ☐ by the effects of electrodynamic forces;
- in IT, on a double fault, the risks inherent in TN described above also exist. However if tracking and elimination of the 1st fault are rapid, installation reliability is excellent.
- in TT, by disruptive breakdown by return of the loads due to a fault in the HV/LV transformers. However the likelihood of this fault occurring is small and preventive solutions are available, e.g. use of surge arresters between one of the live conductors and the load earth connection.

In disturbance terms, the TT is to be preferred to the TN-S whose high fault currents may be the source of disturbance.

a) at the outset

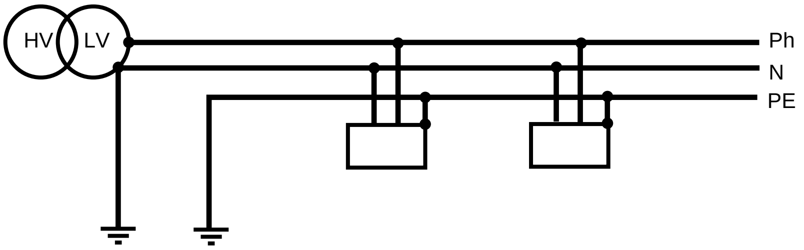


b) in 1960



Multiple RCDs with time discrimination, local equipotentialites and minimum number of earth connections.

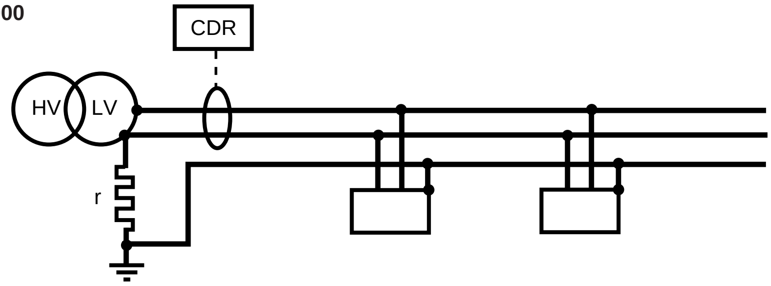
c) in 1990



Same use of RCDs. PE distributed as in TN-S and IT.

In some installations, the two earth connections are connected... it is TN-S without impedance calculation as RCDs are used.

d) 2000



To retain the advantage of the small fault current (damage and EMC), an impedance-earthed TT ($r \approx 12\ \Omega$/Id = 20 A) emerges with a single earth connection. This system requires the use of a surge limiter if the MV zero sequence current exceeds ≈ 80 A - DDRs are used in the same way (time discrimination)

fig. 22: evolution of the TT.

The table in figure 23 reviews the strong and weak points of each earthing system:

For installation designers

Designing is simpler in TT, the same for extensions (no calculations). Designing complexity is equivalent in TN-S and IT.

As regards costs:

- the TN-S is the least costly to install, for example if the neutral is neither protected nor switched. But be warned: the cost of curative maintenance can be high;
- the IT is slightly more costly to install (insulation monitoring and insulation fault tracking devices). Search for maximum availability of electrical power requires the presence of an electrical engineer, whose action will minimise curative maintenance;
- the TT, if enough discriminating RCDs are installed, is slightly more costly to install than the IT, but fault tracking is simple and curative maintenance less costly than in TN.

In terms of complete cost over 10 to 20 years, all three earthing systems are equivalent.

The right choice

In a certain number of countries, for some buildings or parts of a building, the choice is laid down by legislations or standards, e.g. for hospitals, schools, navy, worksites, mines, etc.

In other cases, certain earthing systems are strictly prohibited, for example the TN-C in premises with explosion risks.

Apart from these compulsory choices, the DEPENDABILITY objectives (safety, availability, reliability, maintenability and proper operation of low current communicating systems) are those which should determine which earthing system is chosen for a specific building type.

The degree of development of the country should also be taken into consideration, as should be national practices, climate.... If we plot an axis from North to South, as regards public distribution, we find the IT earthing system in Norway, TN-C in Germany, TT in France and in most African countries.

In temperate, industrialised countries, all three earthing systems are used in private installations.

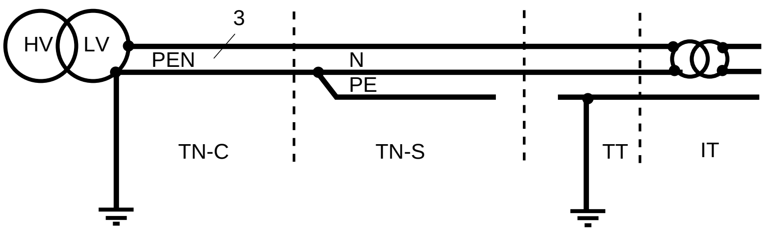
Finally, it should be noted that it is possible and even advisable to mix the earthing systems (see fig. 24).

	TN-C	TN-S	TT	IT(1)	IT(2)	Observations
safety						
■ of persons	+	+	+	++	-	Uc # 0 on 1^{st} fault (IT)
■ fire	- -	-	+	++	-	TN-C not recommended
■ explosions	- -	-	+	++	-	TN-C strictly prohibited
availability- (further to 1 fault)	+	+	+	++	+	depends on discrimination of the SCPDs or RCDs (easier to implement)
maintenability	-	-	+	++	-	the IT authorises preventive and even predictive maintenance
reliability of the installation	-	+	++	++	+	advantage for small Ids (damage- electrodynamic forces)
disturbances						
■ radiation transmission EM	-	-	+	++	-	advantage for small Id
■ equipotentiality of PE	- -	+	++	+	+	pay attention to harmonics in TN-C

(1) : 1^{st} insulation fault.
(2) : 2^{nd} fault.

fig. 23: comparing the earthing system.

a) "series" association of earthing systems



b) "parallel" association of earthing systems

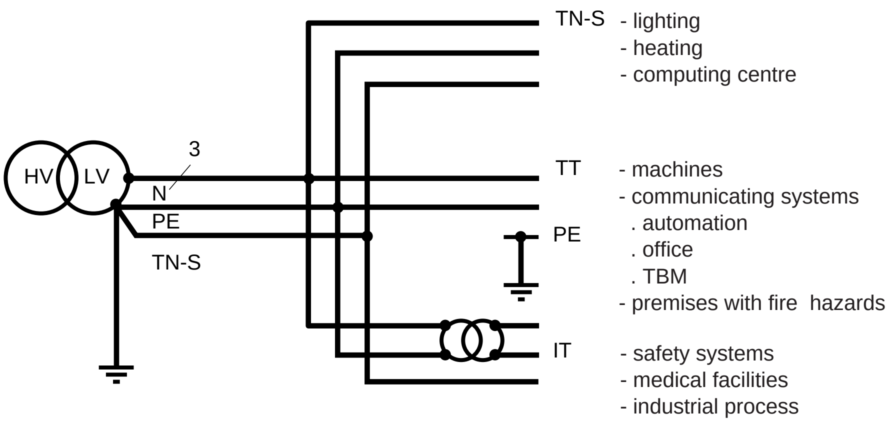


fig. 24: several earthing system included in the same LV installation.

4. conclusion

The three earthing systems (TN - IT - TT) and their implementation are clearly defined in installation standards (IEC 364).

Their respective use varies from country to country:

- mainly TN in Anglo-Saxon countries;
- TT often used in the other countries;
- IT used when safety of persons and property, and continuity of service are essential.

All three systems are considered to guarantee personnel protection.
Two major changes have had a considerable effect on choice of earthing systems:

- search for optimum continuity of service;
- proliferation of high current (disturbers) and low current (disturbed) electronic devices, which are increasingly set up in communicating systems.

Thus the general tendency for earthing systems, in both MV and LV, is to limit insulation fault currents.
At present, the fault currents of traditional LV earthing systems have the following standard values:

- IT (1st fault): Id < 1 A;
- TT: Id ≈ 20 A;
- TN: Id ≈ 20 kA;
- IT (2^{nd} fault): Id ≈ 20 kA.

Limiting fault currents:

- simplifies maintenability of the electrical installation, thus increasing availability;
- minimises the fire hazard;
- can reduce contact voltage;
- and, for sensitive systems, minimises disturbance due to electromagnetic radiation and common impedance.

Moreover, in view of the proliferation of communicating digital systems (computers, video, automation, TBM etc., it is vital that earthing systems provide a potential reference which is not disturbed by high fault currents and harmonics.
Consequently, future evolution should favour earthing systems generating fault currents which do not exceed a few dozen amps.
TT earthing systems should therefore be increasingly used.

appendix 1: IEC 364 standard

■ **364-1** - **Electrical installations of buildings**
(NF C 15-100).

■ **364-1** - 1992
Part 1: **Scope, object and fundamental principles**

■ **364-2-21** - 1993
Part 2: **Definitions** - Chaper 21 - Guide to general terms

■ **364-3** - 1993
Part 3: **Assessment of general characteristics**

■ **364-4**
Part 4: **Protection for safety**

□ **364-4-41** - 1992
Chapter 41 : Protection against Electric Shock

□ **364-4-42**- 1980
Chapter 42: Protection against thermal effects

□ **364-4-43** - 1977
Chapter 43: Protection against overcurrent

□ **364-4-45** - 1984
Chapter 45: Protection against undervoltage

□ **364-4-46** - 1981
Chapter 46: Isolation and switching

□ **364-4-47** - 1981
Chapter 47: Application of protective measures for safety - Section 470: General - Section 471: Measures of protection against Electric Shock

□ **364-4-442** - 1993
Chapter 44: Protection against overvoltages - Section 442: Protection of low-voltage installations against faults between high-voltage systems and earth

□ **364-4-443** - 1993
Chapter 44: Protection against overvoltages - Section 443: Protection against overvoltages of atmospheric origin or due to switching

□ **364-4-473** - 1977
Chapter 47: Application of protective measures for safety - Section 473: Measures of protection against overcurrent

□ **364-4-481** - 1993
Chapter 48: Choice of protective measures as a function of external influences - Section 481: Selection of measures for protection against Electric Shock in relation to external influences

□ **364-4-482** - 1982
Chapter 48: Choice of protective measures as a function of external influences - Section 482: Protection against fire

■ **364-5**
Part 5: **Selection and erection of electrical equipment**.

□ **364-5-51** - 1979
Chapter 51: Common rules

□ **364-5-51** - 1 - 1982
Amendment No. 1
364-5-51 - 1979.

□ **364-5-51** - 2 - 1993
Amendment No. 2
364-5-51 - 1979.

□ **364-5-53** - 1986
Chapter 53: Switchgear and controlgear

□ **364-5-53** - 2 - 1992
Amendment No. 1
364-5-53 - 1986.

□ **364-5-54** - 1980
Chapter 54: Earthing arrangements and protective conductors

□ **364-5-54** - 1 - 1982
Amendment No. 1
364-5-54 - 1980.

□ **364-5-56** - 1980 -
Chapter 56: Safety services

□ **364-5-523** - 1983
Chapter 52: Wiring systems - Section 523: Current-carrying capacities

□ **364-5-537** - 1981
Chapter 53: Switchgear and controlgear - Section 537: Devices for isolation and switching

□ **364-5-537 -** 1 - 1989
Amendment No. 1
364-5-537 - 1981.

■ **364-6**
Part 6: **Verification**

□ **364-6-61** - 1986
Chapter 61: Initial verification

□ **364-6-61** - 1993
Amendment No. 1
364-6-61 - 1986.

■ **364-7**
Part 7: **Requirements for special installations or locations**

□ **364-7-701** - 1984
Section 701: Locations containing a bath tub or shower basin

□ **364-7-702** - 1983
Section 702: Swimming pools

□ **364-7-703** - 1984
Section 703: Locations containing sauna heaters

□ **364-7-704** - 1989
Section 704: Construction and demolition site installations

□ **364-7-705** - 1984
Section 705: Electrical installations of agricultural and horticultural premises

□ **364-7-706** - 1983
Section 706: Restrictive conducting locations

□ **364-7-707** - 1984
Section 707: Earthing requirements for the installation of data processing equipment

□ **364-7-708** - 1988
Section 708: Electrical installations in caravan parks and caravans

appendix 2: bibliography

Standards

- IEC 241: Fuses for domestic and similar purposes.
- IEC 269: Low voltage fuses.
- IEC 364: Electrical installations of buildings.
- IEC 479: Effects of currents flowing through the human body.
- IEC 755: General requirements for residual current operated protective devices.
- IEC 947-2: Low voltage switchgear and controlgear.
- NF C 15-100 : Installations électriques à basse tension.
- NF C 63-080 : Dispositifs de contrôle permanent d'isolement et dispositifs de localisation de défauts associés.
- NF C 63-150 : Limiteurs de surtension : règles.

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