DE1_Appendix IV

MICROGRIDS

Large Scale Integration of Micro-Generation
To Low Voltage Grids

WORK PACKAGE E

REVIEW OF EARTHING IN A MICROGRID

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Nilanga Jayawarna
(UMIST)
M.Lorentzou
S.Papathanassiou
(ICCS)

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1. Introduction

The earthing of an electricity supply network requires its network plant and customer electrical equipment to be connected to the earth in order to promote safety and reduce the possibilities of damage to equipment. Effective earthing prevents long-term over voltages and minimize risk of electric shock hazards. Earthing also provides a predetermined path for earth leakage currents, which are used to disconnect the faulty plant or circuit by operating the protective devices. Research and experience show that both earthed and unearthed electrical systems can be safe. However, earthing of the source neutral is the common practice in Low Voltage (LV) systems.

A MicroGrid is a unique example of a distribution system and as such needs careful assessment before deciding on its earthing system. The first step in this process was identified as reviewing national earthing practices. Two reports have been produced identifying the earthing practices in LV networks and installations. The UMIST report outlines the LV neutral earthing in the UK and mainly refers to the legislations ESQ&C2002, ESR88 (superseded and replaced by ESQ&C Regulations 2002) and BS7671 [1]. The NTUA report reviews the European practices and quotes IEC60364 and French Standard NF C 15-100 [2]. Sections 2- 6 of this document summarises the points raised in these two reports. Section 7 presents the proposed earthing systems for a MicroGrid with their advantages and disadvantages. Section 8 discuses the earthing of the generators in the MicroGrid.

2. Types of earthing systems

A LV distribution system may be identified according to its earthing system. These are defined using the five letters T (*direct connection to earth*), N (*neutral*), C (*combined*), S (*separate*) and I (*isolated from earth*). The first letter denotes how the transformer neutral (supply source) is earthed while the second letter denotes how the metalwork of an installation (frame) is earthed. The third and fourth letters indicate the functions of neutral and protective conductors respectively. There are three possible configurations:

1. TT: transformer neutral earthed and frame earthed
2. TN: transformer neutral earthed, frame connected to neutral
3. IT: unearthed transformer neutral, earthed frame.

The TN system includes three sub-systems: TN-C, TN-S and TN-C-S, as discussed in the following sub-section.

2.1 TN system

In a TN system, the supply source (transformer neutral) is directly connected to earth and all exposed conductive parts of an installation are connected to the neutral conductor. Safety of personnel is guaranteed, but that of property (fire, damage to electrical equipment) is less so. The three sub-systems in TN are described below with their key characteristics.

2.1.1 TN-C earthing system

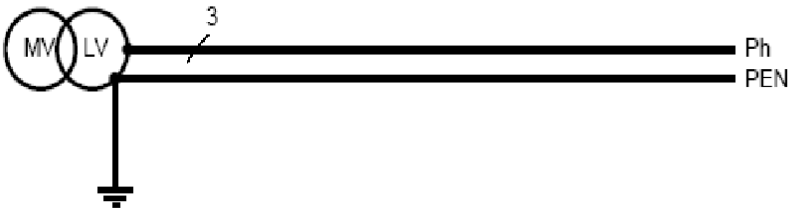


Figure 1: TN-C earthing system

- Neutral and Protective functions are combined in a single conductor throughout the system. (PEN – Protective Earthed Neutral).
- The supply source is directly connected to earth and all exposed conductive parts of an installation are connected to the PEN conductor.
- Particularly used in Anglo-Saxon countries
- Currently not recommended in premises equipped with communicating electronic systems as currents in the neutral and thus in the PE cause potential references to vary.

2.1.2 TN-S earthing system

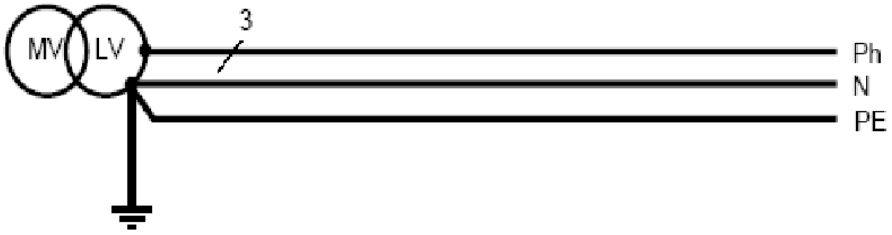
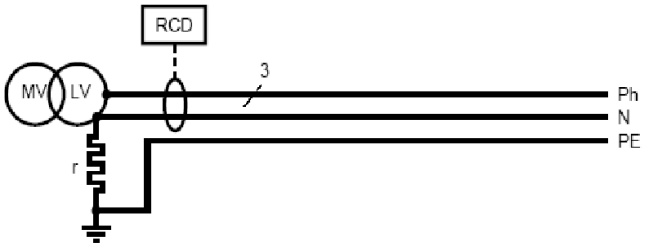
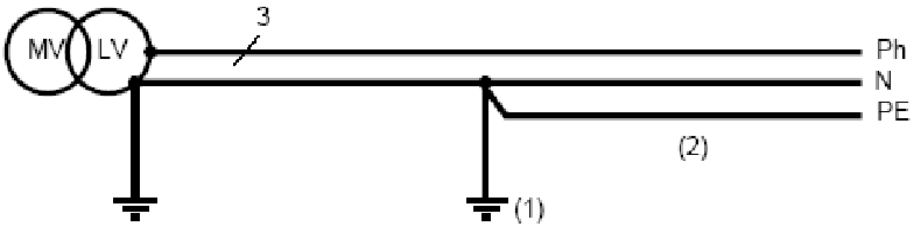


Figure 2: TN-S earthing system

- A TN-S system has separate neutral and protective conductors throughout the system.
- The supply source is directly connected to earth. All exposed conductive parts of an installation are connected to a Protective conductor (PE) via the main earthing terminal of the installation.
- This system is compulsory for networks with conductors of a cross-section $\leq 10 mm^2 Cu$
- Used in Anglo-Saxon countries
- 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. Limits fire risks, damage and potential reference problems for distributed electronics



2.1.3 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 earth. This solution is used in many countries.

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

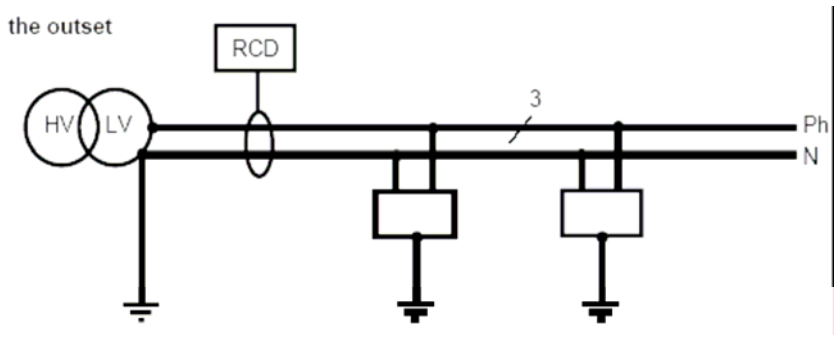
Figure 3: TN-C-S earthing system

- Neutral and protective functions are combined in a single conductor in a part of the TN-C-S system. The supply is TN-C and the arrangement in the installation is TN-S.
- Use of a TN-S downstream from a TN-C.
- All exposed conductive parts of an installation are connected to the PEN conductor via the main earthing terminal and the neutral terminal, these terminals being linked together.
- This is also known as Protective Multiple Earthing (PME) and the PEN conductor is referred to as the Combined Neutral and Earth (CNE) conductor. The supply system PEN conductor is earthed at several points and an earth electrode may be necessary at or near a consumer's installation.

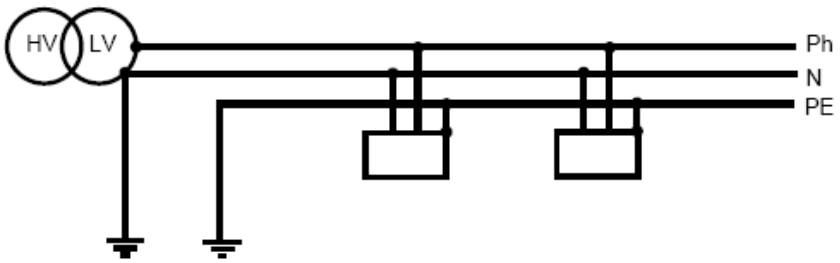
2.2 TT system

The supply source has a direct connection to earth. All exposed conductive parts of an installation also are connected to an earth electrode that is electrically independent of the source earth. The evolution of the TT system is illustrated below [3].

a) At the outset

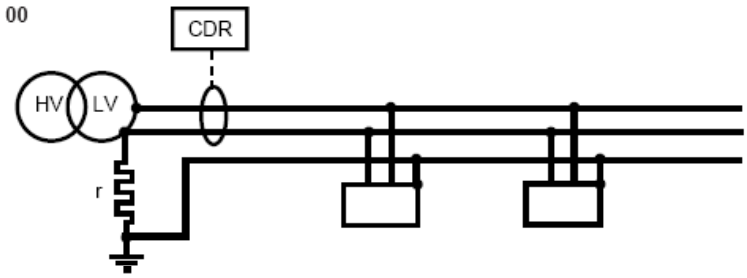


b) In 1990



PE distributed as in TN-S and IT. In some installations, the two earth connections are joined.

c) In 2000



To retain the advantage of the small fault current, an impedance-earthed TT (r ≈12 Ω/Id = 20 A) has emerged with a single earth connection. This system requires the use of a surge limiter if the MV zero sequence current exceeds ≈80 A

Figure 4: TT earthing system [3]

(a): at the outset (b): In 1990's (c): In 2000

2.3 IT system

The supply source is either connected to earth through deliberately introduced high earthing impedance (Impedance earthed IT system) or is isolated from earth. All exposed conductive parts of an installation are connected to an earth electrode.

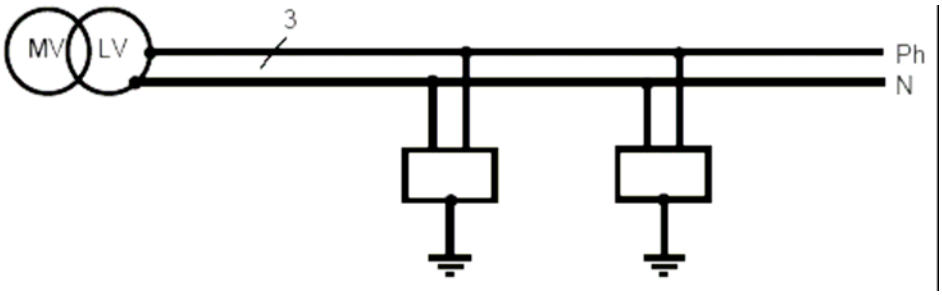


Figure 5: IT earthing system

Every exposed-conductive part shall be earthed to satisfy the following condition for each circuit

$$R_b * I_d \leq 50V$$

Where

R_b = The resistances of the earth electrode for exposed conductive-parts

I_d = Fault current which takes account of leakage currents and the total earthing impedance of the electrical installation

Each earthing system can be applied to an entire LV electrical installation or several earthing systems may be included in the same installation. Figure 6 shows an example of various earthing systems included in the same installation.

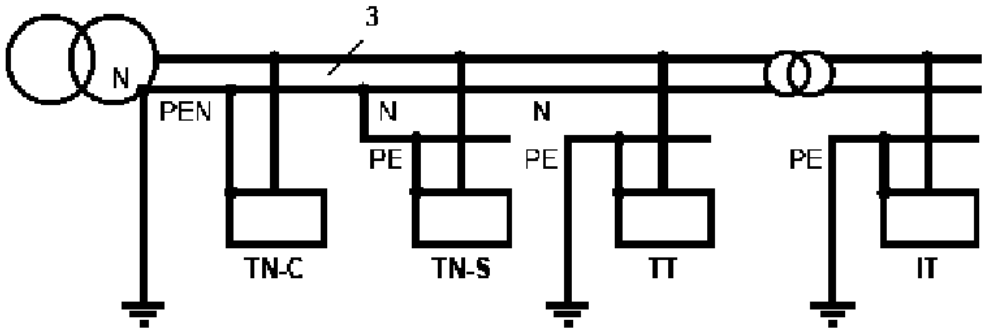


Fig. 6: example of the various earthing systems included in the same installation

3. Fault behaviour and characteristics of different earthing systems

An insulation fault in an electrical installation presents hazards to humans and equipment. At the same time it may cause unavailability of electrical power. The fault currents and voltages differ from one earthing system to another.

3.1 A fault in a TN system

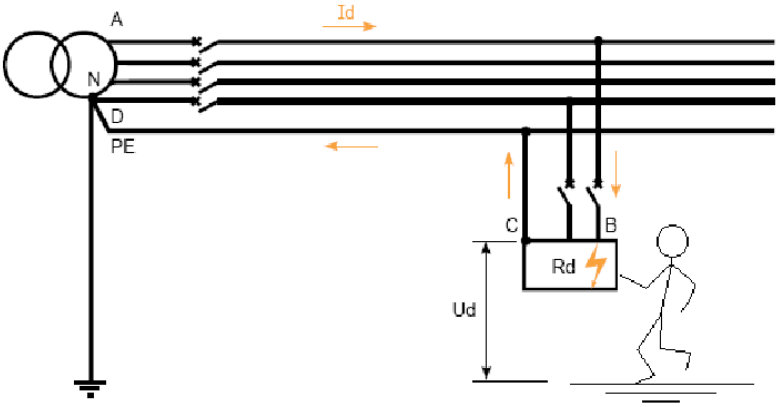


Figure 7: A fault in a TN system

- When an insulation fault is present, the fault current Id is only limited by the impedance of the fault loop cables
- SCPDs (circuit breaker or fuses) generally provide protection against insulation faults, with automatic tripping according to a specified maximum breaking time (depending on phase-to-neutral voltage Uo). Typical breaking times in a TN system are tabulated in Table 1 according to IEC 60364.

Uo (volts) phase/neutral voltage	breaking time (seconds) U_L = 50 V	breaking time (seconds) U_L = 25 V
127	0.8	0.35
230	0.4	0.2
400	0.2	0.05
≧ 400	0.1	0.02

Table 1: breaking time in TN system (taken from IEC 60364 tables 41 and 48A)

3.2 A fault in a TT system

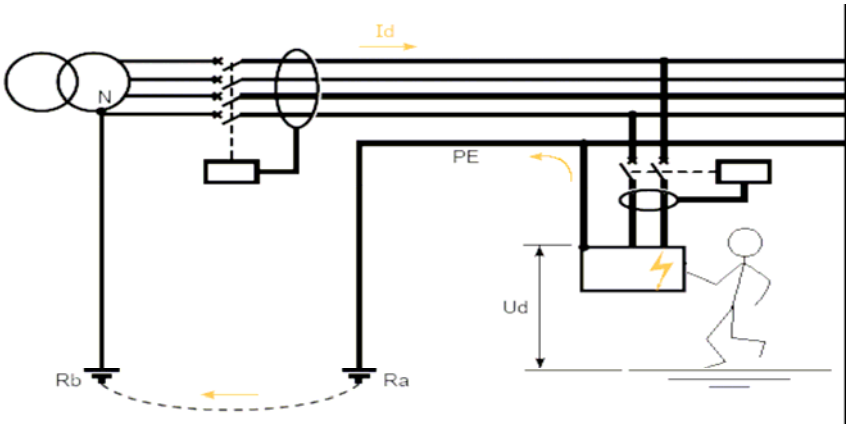


Figure 8: A fault in a TT system

- When an insulation fault occurs, the fault current Id is mainly limited by the earth resistances
- At least one RCD must be fitted at the supply end of the installation. In order to increase availability of electrical power, use of several RCDs ensures time and current discrimination on tripping.

$I\Delta n \leqslant \frac{U_L}{Ra}$ maximum resistance of earth connection		
U_L	50 V	25 V
3 A	16 Ω	8 Ω
1 A	50 Ω	25 Ω
500 mA	100 Ω	50 Ω
300 mA	166 Ω	83 Ω
30 mA	1,660 Ω	833 Ω

Table 2: upper limit of the resistance of the frame earth connection not to be exceeded according to RCD sensitivity and limit voltage UL [I Dn = F(Ra)]

3.3 A fault in an IT system

First fault on an IT system

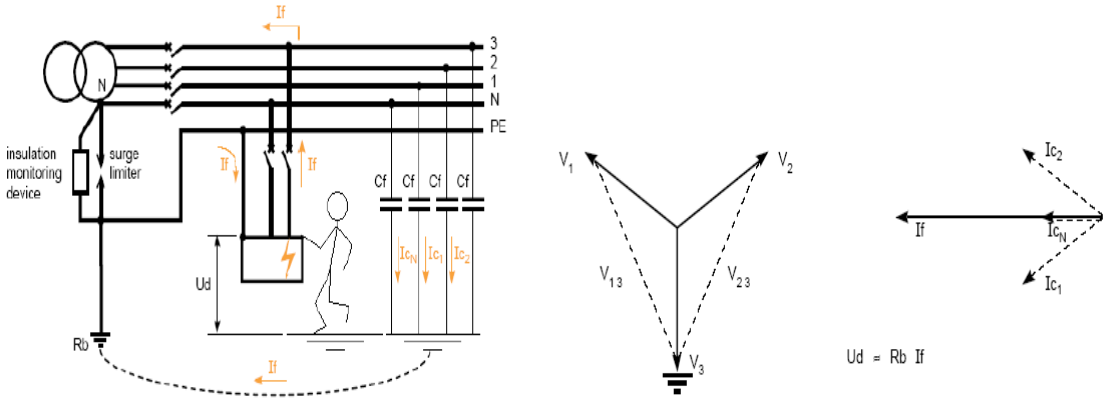


Fig. 9: first insulation fault current in IT system

- The fault voltage is low and not dangerous. Therefore it is not necessary to disconnect an installation in the event of a single fault.
- However it is essential to know that there is a fault and to track it and eliminate it promptly, before a second fault occurs. To meet this need the fault information is provided by an Insulation Monitoring Device (IMD) monitoring all live conductors, including the neutral. Locating is performed by means of fault trackers.
- When the neutral is not distributed (three-phase three-wire distribution)

$$Z_s \leq \frac{0.866U_0}{I_a}$$

- When the neutral is distributed (three-phase four-wire distribution and single phase distribution)

$$Z_s^1 \leq \frac{0.5U_0}{I_a}$$

Where

Z_s = Earth fault loop impedance comprising the phase conductor and the protective conductor

Z_s^1 = Earth fault loop impedance comprising the neutral conductor and the protective conductor

I_a = Fault current

Second fault on an IT system

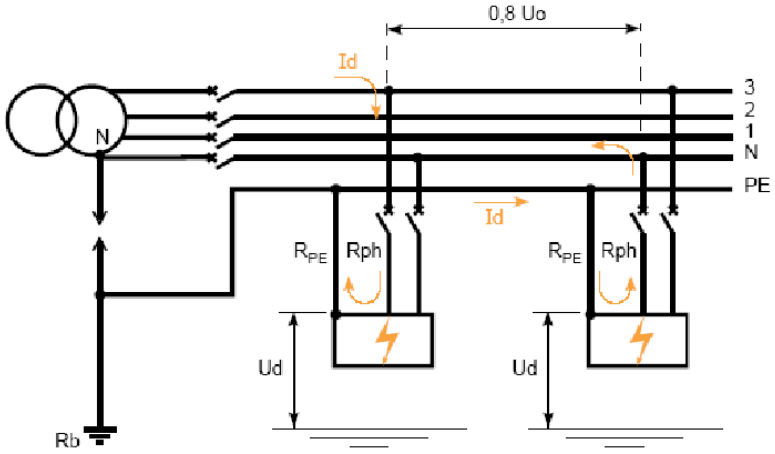


Fig. 10: 2nd insulation fault current in IT system (distributed neutral) and relevant feeders with the same cross-section and length.

Maximum disconnection times for an IT system are given in Table 3 (as in IEC 60364 tables 41B and 48A).

Uo/U (volts) Uo: phase/neutral voltage U: phase to phase voltage	U_L = 50 V breaking time (seconds) Neutral not distributed	 Neutral distributed	U_L = 25 V breaking time (seconds) Neutral not distributed	 Neutral distributed
127/220	0.8	5	0.4	1.00
230/400	0.4	0.8	0.2	0.5
400/690	0.2	0.4	0.06	0.2
580/1 000	0.1	0.2	0.02	0.08

Table 3: Maximum disconnection time in IT systems (second fault)

3.4 Fault characteristic quantities of earthing systems

In order to overview of the quantities characterising the various earthing systems, as regards protection of persons, the main formulas are listed in Table 4.

		Id	Ud	Lmax	continuity of service
TN		$\frac{0.8\ Uo\ Sph}{\rho\ (1+m)\ L}$	$\frac{0.8\ Uo}{1+m}$	$\frac{0.8\ Uo\ Sph}{\rho\ (1+m)\ Ia}$	vertical discrimination
TT		$\frac{Uo}{Ra+Rb}$	$\frac{Uo\ Ra}{Ra+Rb}$	no constraint	vertical discrimination
IT	1st fault	< 1 A	<< U_L		no tripping
	double fault with neutral	$\leqslant \frac{1}{2}\ \frac{0.8\ Uo\ Sph}{\rho\ (1+m)\ L}$	$\leqslant \frac{m}{2}\ \frac{0.8\ Uo}{1+m}$	$\frac{1}{2}\ \frac{0.8\ Uo\ Sph}{\rho\ (1+m)\ Ia}$	vertical discrimination and possibility of horizontal discrimination to the advantage of hich current feeders
	double fault between phases	$\leqslant \frac{\sqrt{3}}{2}\ \frac{0.8\ Uo\ Sph}{\rho\ (1+m)\ L}$	$\leqslant \frac{m\ \sqrt{3}}{2}\ \frac{0.8\ Uo}{1+m}$	$\frac{\sqrt{3}}{2}\ \frac{0.8\ Uo\ Sph}{\rho\ (1+m)\ Ia}$	

Remember that:

- $\rho = 22\ 10^{-6}\ \Omega/mm^2/m$ for Cu (36 for Al);
- $m = \frac{Sph}{S_{PE}}$;
- PE cross-section, normally equal to phase cross-section, can be equal to half of phase cross-section when the latter exceeds 35 mm^2.... thus increasing Ud in TN and IT.

Table 4: characteristic quantities of earthing systems [4]

Where

U_L = Limit voltage/ safety voltage

U_d = Fault voltage

R_a = Resistance of the installation earth

R_b = Resistance of the source earth

I_d = Fault current

I_a = Automatic breaking current

U_0 = Phase-to-neutral voltage

L_{max} = Maximum length in m

The standard values for fault currents in traditional LV earthing systems are as follows.

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

4. Suitable switchgear selection

Suitable switchgear has to be selected for protection purposes. These are described below for each earthing system.

4.1 TN system

Short-Circuit Protection Devices (SCPDs - circuit-breaker or fuses) generally provide protection against insulation faults, with automatic tripping according to a specified maximum breaking time.

4.2 TT system

The low fault currents do not allow the SCPDs to protect persons against indirect contact. Residual Current Devices (RCDs) need to be used, associated with circuit breakers or switches.

4.3 IT system

Insulation Monitoring Devices (IMDs) are used for locating the first fault. In the occurrence of a second fault, automatic breaking is vital due to the electric shock risk: this is then the role of the SCPDs backed up by the RCDs if required. This system must also be protected against risks of insulation faults between MV and LV by a surge limiter.

4.4 Neutral Protection

A multi-pole device must break the neutral

- In TT and TN, if neutral cross-section is less than phase cross-section
- In terminal distribution in view of the Neutral/ Phase reversal risk.

The neutral must be protected and broken

- In IT for intervention of the protection device on the double fault, with one of the faults possibly on the neutral
- In TT and TN-S if neutral cross-section is less than phase cross-section
- For all earthing systems if the installation generates harmonic currents of order 3 and multiples (especially if neutral cross-section is reduced).

In TN-C, the neutral, which is also the PE, cannot be broken which would be dangerous as a result of its potential variations, due to load currents and insulation fault currents. To prevent risks, a local equipotential bonding and an earth connection must be provided for each zone/consumer.

Figure 11 shows which types of circuit breaker should be used for which earthing system [4]. Note that TT and TN can use the same devices, with an additional RCD in TT systems.

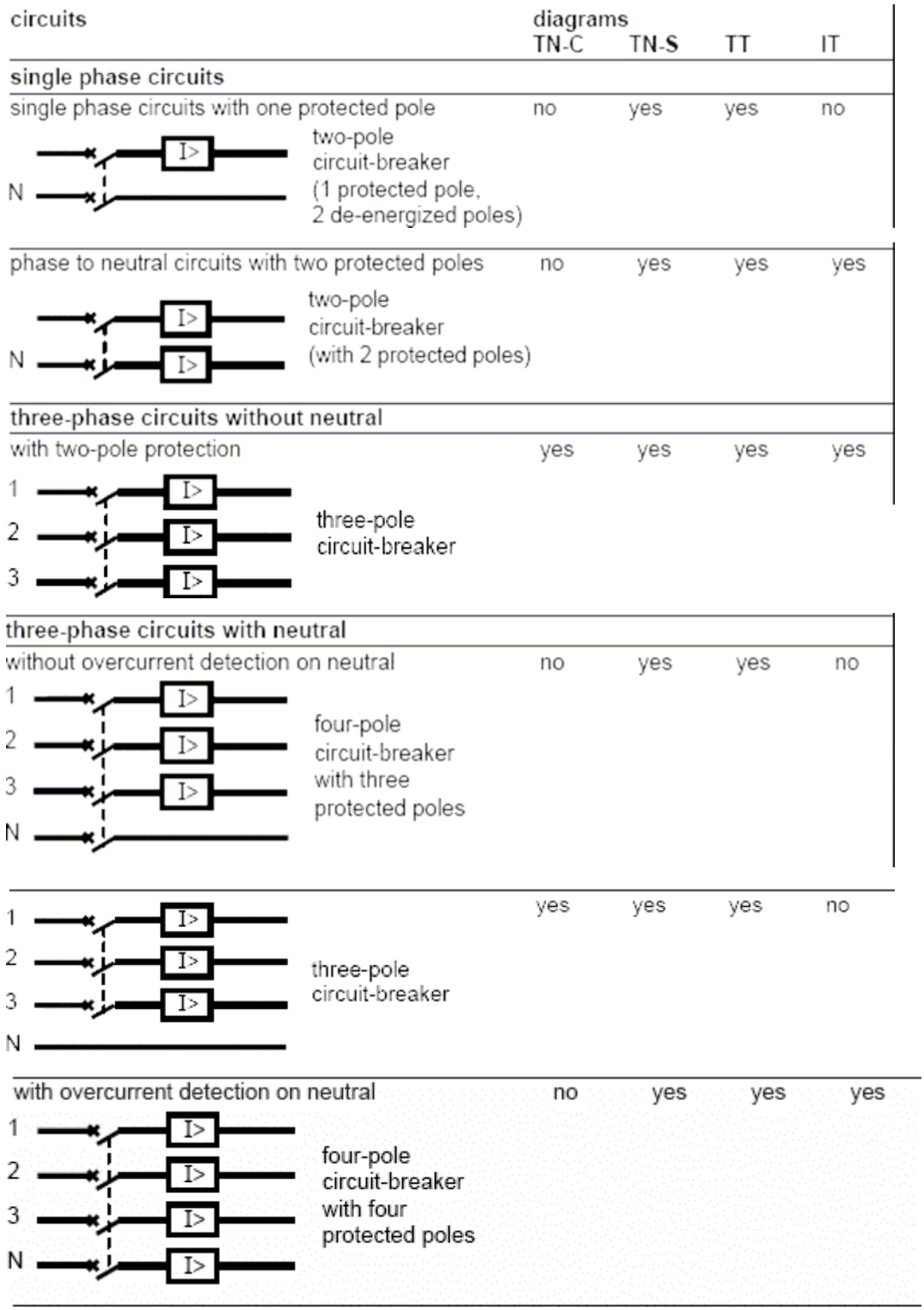


Figure 11: Examples of circuit-breakers according to earthing systems [4]

5. Review of International Standards and Practices in LV earthing

Table 5 gives the various earthing systems used in LV public distribution systems in different countries

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).

Table 5:Public distribution examples worldwide – LV earthing systems [3]

According to the above table, TT seems to be the most common earthing system used. At the same time, we have to make note of two points. Firstly, where both TN and TT systems are found (for example, Germany and Great Britain), TN is the principal earthing system and TT is not used often. Secondly the recent trends show that many countries are moving away from TT and adopting TN systems (for example, Netherlands and Portugal) for the reason of greater reliability.

6. Selection of the suitable earthing system

Choice of the LV earthing is usually determined by the normal practice in the country. Although the design engineers make the decisions, electrical power users and network operators should influence this choice. Users and operators both demand absolute dependability. The elements making up installation dependability are safety,

availability, reliability and maintainability. In addition, electricity must not disturb the numerous low current devices.

These are the criteria used to make the best choice and it is summarized in Table 6 for each earthing system [3].

	TN-C	TN-S	TT	IT(1)	IT(2)	Observations
safety						
■ of persons	+	+	+	++	-	Uc # 0 on 1st 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) : 1st insulation fault.
(2) : 2nd fault.

Table 6: comparison of the earthing systems [3]

In safety terms**,** the TT is the best option while IT gives the greatest availability**.** In maintainability terms**,** fault locating is fast in TN (thanks to the SCPD) but repair time is often long. Conversely, in IT, locating the first fault may be more difficult, but repairs are quicker and less costly. The TT is a good compromise. In disturbance terms, the TT is to be preferred to the TN-S whose high fault currents may be the source of disturbance. All the earthing systems are approximately equivalent in terms of complete cost over 10 – 20 years

In some countries, for some buildings or parts of a building, the choice of the earthing system is laid down by legislations or standards, e.g. for hospitals, schools, naval places, 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 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. It should also be noted that it is possible and even advisable to mix the earthing systems

7. Neutral earthing in the MicroGrid

A range of options is available to earth the MicroGrid network as explained in the above sections. The most common systems are TT and TN; a few countries, in particular Norway, use the IT system. Generally, global use of different earthing systems is as follows;

- 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.

When selecting the neutral earthing method for a MicroGrid, following factors need to be considered initially.

1. *What is the normal practice in the country?*

   If an alternative system were to be introduced in the MicroGrid, all involved personnel would have to be trained on the new system. They might not be willing to deviate from the system they are accustomed to and the training programmes will introduce additional costs.

2. *What are the legislations to be adhered to?*

   Most countries apply or derive the systems from standard IEC 60364. However, each country might have their particular statutory orders. For example, "Electricity, safety, Quality and Continuity Regulations 2002 (ESQ&C2002)" and BS 7671 are the key legislations in UK in this field.

3. *What are the foremost needs of the MicroGrid customers?*

   The choice of the earthing system would depend on the needs of the network consumers. If availability is essential above all else, IT system might have to be used. If safety is the chief requirement, TT is probably the best option.

It has to be remembered that the MicroGrid could adopt a single earthing system or a combination of systems according to its individual needs. Generally considering, the most appropriate earthing system for a typical MicroGrid is either TN (most specifically TN-C-S) or TT. This choice could be different for individual MicroGrids in keeping with the above-mentioned three issues. The pros and cons of these two systems are summarized below

7.1 TN System in a MicroGrid

7.1.1 Advantages of a TN system

1. A TN system always provides a return path for faults in the LV grid. The grounding conductors at the transformer and at all customers are interconnected. This ensures a distributed grounding and reduces the risk of a customer not having a safe grounding.
2. Lower earthing resistance of the PEN conductor
3. TN systems has the advantage that in case of an insulation fault, the fault voltages are generally smaller than in TT systems. This is due to the voltage drop in the phase conductor and the lower impedance of the PEN conductor compared with the consumer earthing in TT systems
4. No overvoltage stress on equipment insulation
5. TN-S system has the best EMC properties for 50Hz and HF currents, certainly when LV cable with a grounded sheath is applied
6. TN could work with simple overcurrent protection
7. High reliability of disconnection of a fault by overcurrent devices
8. Highest attainable protection level could be achieved with an overcurrent device along with a RCD if required.
9. Compensation of the earthing effect of old gas and water pipes, which are now made of plastic materials

7.1.2 Disadvantages of a TN system

1. Faults in the electrical network at a higher voltage level may migrate into the LV grid grounding causing touch voltages at LV customers.
2. A fault in the LV network may cause touch voltages at other LV customers

3. Potential rise of exposed conductive parts with the neutral conductor in the event of a break of the neutral network conductor as well as for LV network phase to neutral and phase to ground faults and MV to LV faults
4. The utility is not only responsible for a proper grounding but also for the safety of customers during disturbances in the power grid
5. Protection to be fitted in case of network modification (increase of fault loop impedance)
6. TN-C system is less effective for Electromagnetic Compatibility (EMC) problems

7.2 TT system in a MicroGrid

7.2.1 Advantages of a TT system

1. The most commonly found earthing system
2. Faults in the LV and MV grid do not migrate to other customers in the LV grid
3. Good security condition, as the potential rise of the grounded conductive part must be limited at 50 V for a fault inside the installation and at 0V for a fault on the network.
4. Simple earthing of the installation and the easiest to implement.
5. No influence of extending the network.

7.2.2 Disadvantages of a TT system

1. Each customer needs to install and maintain its own ground electrode. Safety and protection depends on the customer, thus complete reliability is not assured.
2. High overvoltages may occur between all live parts and between live parts and PE conductor
3. Possible overvoltage stress on equipment insulation of the installation
4. For large customers it is impossible to apply a TT system, since the disconnecting time of the over-current protective device is too long
5. RCD is considered as being a good protection against resistive short circuits or indirect contact. However, it is highlighted that its failure rate may not be negligible and is higher than that of overcurrent protections

8. Earthing of the micro-sources

An embedded generator could operate with its neutral point earthed or not earthed [5-7]. However, the provision of an earthing reference is important for the micro-sources, for both grid-connected operation and islanded operation. This is an important fact to consider in design of the MicroGrid.

Several options for generator neutral point earthing and relevant legislations are described in Engineering Technical report ETR113 and the British Standards BS7430 [5, 8]. There are a number of methods available to earth the generators, as given below.

1. Switched neutral point earthing
2. Impedance earthing
    a. Direct (solid) earthing
    b. Resistance earthing
    c. Reactor earthing
3. Via a Voltage Transformer (VT) with residual voltage or neutral voltage displacement protection
4. Transformer earthing

According to current legislations, LV generators may be earthed or unearthed when operating in parallel with the distribution system. The usual practice is not to earth the generator neutral point in parallel operation. In a typical MicroGrid there would be several generators dispersed throughout the system. If all or some of these generators are connected to earth, the following technical issues have to be considered due to multiple earthing [9].

- Control of earth fault currents
- Maintaining predetermined paths for earth fault current
- Detection of earth leakage currents
- Effectiveness of network earthing
- Limiting circulating currents at fundamental and harmonic frequencies
- Avoiding interference to communication systems

Due to the above issues, earthing of micro-sources in grid-connected operation is not desirable at all.

In the case of the generators in a MicroGrid not being earthed, we must ensure that an earth reference point is provided when the MicroGrid is disconnected from the main grid. One possible solution is to operate the generator with an unearthed start point when grid-connected and then automatically reconnect the start point to neutral/ earth connections when the MicroGrid is islanded. The MicroGrid Central Controller (MGCC) could send down a signal to all the micro-sources when the MicroGrid is disconnected from the distribution system or when it is reconnected. The generator neutral earth could be switched according to this signal.

Proposed protection schemes for a MicroGrid describe three operating scenarios according to the location of the fault [10].

1. For a fault on the distribution system, the MicroGrid will continue to operate in an island by opening the circuit breaker upstream of the main distribution transformer.
2. For a fault on the MicroGrid network, the whole MicroGrid will discontinue its operation. Sectionalising of a general MicroGrid is not advised.
3. For a fault at a residential consumer, the relevant consumer would be disconnected from the MicroGrid, and normal operation would continue.

According to above protection guidelines, the MicroGrid would not lose the source earth at the distribution transformer in any event. Therefore, the micro-sources do not require to be earthed.

9. Conclusions

A MicroGrid must achieve the same level of safety as any other conventional distribution system. Therefore the grounding of the distributed energy sources, and the transformer connecting the MicroGrid to the utility network, requires to be carefully analyzed and appropriate rules need to be developed. An extensive literature review had been carried out. According to this analysis, the most suitable earthing systems for a MicroGrid are identified as follows in the order of their suitability.

1. TN-C-S
2. TT
3. IT

The performance of each of these earthing systems in a MicroGrid needs to be further investigated via simulation.

As per proposed protection guidelines for a MicroGrid, it would not lose the source earth at the distribution transformer in any event. Accordingly, the micro-sources do not require to be earthed.

10. References

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