Ensuring public safety through proper earthing in low-voltage networks

Citation for published version (APA):

Bhattacharyya, S., & Cobben, S. (2017). Ensuring public safety through proper earthing in low-voltage networks. *CIREN - Open Access Proceedings Journal*, 2017(1), 617-620. <https://doi.org/10.1049/oap-cired.2017.1261>

DOI:

[10.1049/oap-cired.2017.1261](https://doi.org/10.1049/oap-cired.2017.1261)

Document status and date:

Published: 01/10/2017

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Ensuring public safety through proper earthing in low-voltage networks

Sharmistha Bhattacharyya¹ ✉, Sief Cobben²

¹Enexis, Asset management department, 's-Hertogenbosch, The Netherlands

²Technical University of Eindhoven, Electrical Engineering department (EES group), Eindhoven, The Netherlands

✉ E-mail: sharmirb@yahoo.com

Abstract: Electrical network should have proper earthing (grounding) system for its reliable operation and for the safety of operating personnel and connected customers. Good earthing provides a suitable return path for the fault current when a short circuit occurs in the network. In a low-voltage (LV) network mainly terra-terra (TT) and terra-neutral (TN) type network configurations are commonly used. Depending on the agreement between the network operator and the customer, earthing at a customer's point of connection (POC) is provided by a dedicated earth conductor, combined network cable (PEN conductor), or via a separate earth electrode. When an earth return path is broken or interrupted, it will not be able to provide earth return circuit and can cause dangerous fault voltage at various exposed parts of the conducting circuit. In this paper, various LV network configurations are discussed. Further, a practical monitoring based case study is presented to analyze the diversity of earth resistance values for different LV network configurations. Also, guiding rules are given to define safe value of circuit impedance and earth resistance path for various configurations. Finally, a proposal is given to optimize the safety needs at a customer's POC.

1 Introduction

The low-voltage (LV) network can be of various configurations depending on network operator's design strategy and operational philosophy. Proper earthing of an electricity network is an utmost need for ensuring safe work environment for the operating and maintenance personnel and public safety preventing unpleasant electric shocks and fatal accidents. Good earthing provides a suitable return path for the fault current when a phase to earth short circuit occurs in the network. It is also needed for reliable operation of the network components. However, a good earthing system can be damaged because of breakage of the continuity of earth conductor due to various digging activities by different facility services (such as water supply, telecom services, utility services etc.) or sometimes due to stealing of earth copper wire or because of some other reasons.

In a LV network, two types of network configurations are commonly used: terra-terra (TT) and terra-neutral (TN) configuration. For a TT system, the network operator does not provide the earthing system to the customer. Hence, the customer himself is responsible for arranging proper safety measures of his installation. The design of earthing system of a customer's installation is largely dependent on network impedance and the supply side earth impedance. In a TN system, the network operator provides an earth connection point and the customer can connect his installation to that point for a safe earthing network. In this case, the network operator is responsible to provide an adequate low resistance earth path for the installation. For LV installations, the Dutch standard NEN1010 [1] (comparable with IEC 60364- series) is applicable which gives guidelines for safe operating condition in both TT and TN system. The customer must follow this standard while designing his installation.

In a TN system, the network operator must design the earth path with utmost care and should monitor and maintain it regularly, depending on the design of the earthing system. An earth path in TN system can be served via separate dedicated earth conductor (TN-S system) or via a combined neutral-earth conductor (TN-C system). In the last decades, also metal pipelines were used but they are slowly replaced by plastic pipelines that do not conduct electricity. Therefore, the existing earth

connection for the customers might be discontinued and needs to be replaced by new earth conductors or by other means. The electricity, gas, telecom and water service companies generally work in close operation to maintain and restore the utility infrastructure optimally. However, because of occasional miscommunication, the earthing system are left broken that may lead to potential unsafe conditions. As per the Dutch regulation, the short circuit fault voltage in a LV network should be limited to 66 V or the fault has to be cleared within 5 s by the protective device present in the network, as shown in Fig. 1 [2]. These guidelines are now applicable for the new but could also become applicable for the old LV networks in the Netherlands. Nationwide the network operators are facing challenges to fulfil these guidelines for their networks.

In this paper, first various LV network configurations are discussed. A practical monitoring based case study is presented to analyse the diversity of earth resistance values for different network configurations. Further, guiding rules are given for the safe value of circuit impedance for various network configurations. Finally, a proposal is given to optimise the safety needs at a customer's point of connection (POC).

2 LV network configurations

Typical LV network configuration can be mainly of two types: (i) TT-earthed system (where the installation is earthed at customer's location by a separate earth electrode), (ii) TN-earthed system (where the earthing connection is provided by the network operator and the customer may use it). Earthing at the source side of the electric supply is also done by the network operators. Hence, they are responsible to guarantee a safe electric supply in various parts of the network, at the customer's terminals and public areas.

2.1 TT-earthed system

In a TT configuration, the network operator does not provide an earth connection point to the customer. Therefore, the customer has to

Fig. 1 Safety regulation in the LV networks of the Netherlands

arrange an appropriate earth electrode so that his installation can operate safely and fulfil the standard safety limits specified in the Dutch LV installation guidelines NEN 1010 (comparable with IEC 60364-series). From the mid-1990s, a residual current device is highly recommended by this standard to ensure additional safety of the customer's installation against direct and indirect shock hazards.

Fig. 2 shows a general TT circuit along with its earth connection points and the equivalent impedance circuit diagram. At the LV side of transformer station, the star point is grounded by resistance R_b . The line impedance of the cable is represented by Z_l and the earth electrode (including the impedance of the PE-conductor) at the customer terminal is named as R_a . The value of total circuit impedance (Z_c) is summation of $R_b + Z_l + R_a$, as shown in Fig. 2. The value of $R_b + Z_l$ is decided by the network operator and is restricted to a maximum value of 0.9Ω as per NPR 5310 (2008) which is the practical Dutch installation guide for NEN 1010. The value of R_b is restricted to 0.4Ω . In Section 3 the maximum value of R_a for various types of LV installations are shown (Table 2). From the fault-tripping characteristic of the protective device connected at the installation of the customer, it is possible to choose the current value at which the fuse would trip the fault current. According to NEN 1010, for TT system the fault should be cleared within 0.4 s (when potential bonding is used) for LV installation, while for the distribution group, it is restricted to 1 s.

2.2 TN-earthed system

In a TN configuration, there is a possibility to connect the earth connection point of the customer's installation with the network's earth. If the customer chooses to connect his earth point to the network's earth connection, then he does not need to install a separate earth electrode at his installation.

A TN system can also be sub-categorised in two groups: TN-C (combined system, where neutral and protective earth (PE) conductors are coupled together), and TN-S (separate earth system, in which neutral conductor and PE are separated). In TN-C

Fig. 2 TT system and its equivalent impedance diagram

Fig. 3 TN-S system and its equivalent impedance diagram

system, a neutral conductor of the main cable serves the purpose of earthing too (called 'PEN conductor'). In a TN-S configuration, a separate dedicated serves the purpose of earth return path. Both these two systems have their own advantages and disadvantages. In a TN-S system, the neutral and PE conductors are coupled at several points in the network. Thus, it provides extra reliable path for the unbalanced current to return to the source side even when neutral conductor is broken. In a TN-C system, as there is no separate earth conductor, it can have at higher risk to safety issues in case neutral conductor is damaged (during ground digging activity).

As shown in Fig. 3, the circuit impedance (Z_c) in a TN-S system consists of phase conductor (Z_l) and the total impedance of neutral and earth conductor in parallel (Z_{pe}). For a TN-C system, PEN-conductor impedance is the only one considered for return path impedance Z_{pe} .

According to NEN 1010, for a TN system the fault should also be cleared within 0.4 s for LV installation. For distribution group, the maximum switching out time is restricted to 5 s. The maximum fault tripping current is to be selected from the current-time characteristic of the protective device that is connected at the entrance of the customer's installation.

3 Safe value of circuit resistance

The maximum short circuit withstand capability of a protective device at an installation is determined by its current-time characteristic. The following values as shown in Table 1 are used commonly for various types of protection devices at the LV installations in TT-earthing system (as per NPR 5310):

Using the above guidelines, the maximum value of circuit impedance (Z_c) and earth electrode impedance (R_a) at the customer's installation are calculated in Table 2 for TT-earthing system.

From Table 2 it is clear that TT-earthing configuration becomes unrealistic for larger capacity installations (>25 A). The required small value of earth electrode at the customer installation with growing connection capacity becomes a restricting factor to implement TT system. Also, for a TT system, the customer needs

Table 1 Maximum circuit impedance in TT system

Protective device type	Maximum circuit impedance
fuse type: gG- and D-characteristic	$30/I_n$
D-type fuse with delayed response	$22.5/I_n$
circuit breaker with B-characteristic	$40/I_n$
circuit breaker with C-characteristic	$20/I_n$

I_n is the nominal connection capacity of the installation.

Table 2 Maximum values of circuit impedance in TT system

Installation capacity and protection type		Circuit impedance (Z_c), Ω	Maximum value of earth electrode at customer's installation (R_a), Ω
gG-fuse	16A	2.0	1.1
	20A	1.5	0.6
	25A	1.3	0.4
circuit breaker protected	B16	2.9	2.0
	B20	2.3	1.4
	B25	1.8	0.9
	C16	1.4	0.5
	C20	*	*

“*” is given for C20. It means that the value is too low and is not possible to attain in practice. Therefore, it is advised to place a suitable residual current device (RCD) at the entrance of the installation.

Table 3 Maximum circuit impedance in TN system

Protective device type	Maximum circuit impedance
fuse type: gG- and D-characteristic	34/ I_n
D-type fuse with delayed response	30/ I_n
circuit breaker with B-characteristic	46/ I_n
circuit breaker with C-characteristic	23/ I_n

I_n is the nominal connection capacity of the installation.

to check the correct value of earth electrode periodically to ensure that its value stays within the boundary limits as given in Table 2.

Guidelines (NPR 5310) are given for TN-S configuration too and are summarised in Table 3. The allowable fault current boundaries for TN system are bit higher than an equivalent TT system, as a TN earthing system is assumed to be relatively more reliable than a TT system.

Using the guidelines of Table 3, the maximum circuit impedance is calculated for TN-S configured network as shown in Table 4.

From Table 4, it can be seen that as the connection capacity of LV installation increases, the allowable limit for circuit impedance is decreasing. Therefore, the installation has to be located closer to the transformer/supply station or the cross-section of the cables should increase. As a network design guiding rule, restrictions could be given to the maximum value of phase impedance of a LV cable and connection cables depending on their cross-sections.

4 Developments in safety standards

In paper [2] the vision of the Dutch national regulator ‘Autoriteit Consument en Markt’ in Dutch (ACM) about the safety requirements of public networks are discussed briefly. In this section, the latest developments are summarised. ACM expects that every network (old and new) should fulfil at least some minimum safety features. The regional network operators (RNBs) often claim that the new networks are designed following the safety standards more strictly and have better and safer operational performances than the old networks. In contrary, many of the old networks are designed decades ago without precisely considering all these new design standards (fault voltage ≤ 66 V and/or fault clearance ≤ 5 s), but are still performing perfectly. An unsafe

Table 4 Maximum values of circuit impedance in TN system

Protection type	Maximum circuit impedance (Z_c), Ω				
	Installation capacity				
	16 A	20 A	25 A	35 A	40 A
gG- and D fuse	2.13	1.7	1.36	0.97	0.85
D-type fuse with delayed response	1.88	1.5	1.2	0.85	0.75
circuit breaker with B-characteristic	2.88	2.3	1.84	1.31	1.15
circuit breaker with C-characteristic	1.44	1.15	0.92	0.65	0.58

incident is seldom reported in those old network areas. It is agreed between ACM and the RNBs to develop two standards specifically for each type of networks. However, the minimum standard should be applied for both the cases.

The minimum standard should have uniform requirements for all types of networks. When tested for the safety criteria of these networks, the outcomes should be unambiguous and reproducible. The short circuit current of the network should be cleared by the protective device within the maximum specified time limit to avoid unsafe voltage rise at the exposed parts of network components.

With ACM discussion about the needed requirements are during the preparation of this paper still ongoing. According standards the new networks should be designed optimally following the ‘fault voltage lower than 66 V’ or ‘5 s rule’ principle where the fault current should be cleared by the main protective device present in the LV cable within 5 s time or the fault voltage at different network parts should remain within the safe limit of 66 V. For the existing networks, if these rules cannot be achieved, sufficient measures should be taken so that no part of the network remains unsafe. Finally, safety management system is to be implemented in which a structural method would be applied to monitor the network periodically (by control checks through site measurement). By this check, it can be guaranteed that the safety guidelines are met for all parts of the networks. When it is found that the network does not fulfil the safety guidelines, proper mitigation measures need to be taken to bring down the risk with in an acceptable limit.

5 Monitoring network resistance

As discussed above, the regulatory body ACM wants a guarantee from the RNBs that their networks are safe in short-circuit fault condition. To check this criterion, one way is to measure network circuit impedance. In the paper [2], detailed description is given about the safe value of circuit impedance calculation to achieve maximum safety at a network point. However, the maximum value of circuit resistance at a customer's connection point is dependent on many factors in the network: main protection device (fuse) characteristic and its rating, the features of main network cable, the connection cable length, return path configuration etc. By considering all these factors, it is decided to use 0.5Ω as a realistic circuit impedance value for LV installations connected to a TN network.

In this paper, a specific city in the Netherlands is considered where more than 110,000 LV electricity users are connected. Majority of the LV network of this area is TN configured where the network operator provides an earth point to the customer at the time of the connection to the installation. At that time, the network operator guarantees that the earth resistance is low enough and provides a safe return path if a short circuit occurs in the network. For any internal faults inside the installation, the customer should himself take sufficient measures.

The LV network of this specified region is messed configured in which the earthing conductors are connected with different parts of the network. This makes the earth return circuit more reliable. Nevertheless, it also gives a need for proper design of the LV network itself.

A standard LV cable consists of three phase conductors and a neutral conductor. Earthing can be served by the neutral conductor or by a separate earth conductor. In the older generation networks, lead sheath of the cable or a nearby metallic pipeline is also used for main earthing. The connection cable up to the installation consists of phase and neutral conductors that carry main currents. At the outer side of connection cable has litz wires which is mainly used to support the cable but can also be used for earthing. Hence, the total earthing circuit up to a LV customer's POC consists of two parts: (i) earthing of main cable and (ii) earthing of connection cable. In Table 5, various combination of earthing methods that are used in this specific network are summarised.

From the internal asset database [3], it is found that >65% of the networks have separate earth conductor earthing system (TN-S),

Table 5 Various combination of earthing methods in main and connection cables

Earthing method used in main cable	Earthing method used in connection cable			
	Separate earth conductor	Litz of connection cable	Lead sheath of cable	Water pipeline
separate earth conductor	Yes ^a	Yes ^a	Yes ^a	Yes
neutral conductor	Yes	Yes ^a	—	—
lead sheath of main cable	Yes	—	Yes	—
water/gas pipelines	Yes	—	Yes	Yes ^a

^aIndicates that these are majority in numbers (minimum > 1000).

Table 6 Distribution of earthing types for connection cables

Connection cable-earthing method	Percentage of total, %
separate earth conductor	49.60
litz of connection cable	29.90
lead sheath of cable	10.90
water pipelines	9.50
earth electrode	0.10
total	100

while around 15% have TN-C system where PEN conductor is used for earthing. Around 10% of the population has earthing that uses water pipelines. In the last years, lead sheath main LV cables are gradually being replaced from the network, and only a small population (mainly connection cables) is still in operation. Besides the above, there is also a very small population (around 0.1%) of the customers that have their own earth electrodes at their installations (TT system). In Table 6, the distribution of various earthing methods for connection cables is summarised.

In the last few years, monitoring programme [3] has been started to determine actual circuit impedance at various connection points.

From the big population of LV cables, a sample size is selected for site measurement. In this programme, all types of networks are selected to get an estimation of the actual situation of existing networks. It is decided that any connection point should be measured twice if circuit impedance is found $Z_c > 1 \Omega$. In addition, additional measurements would be done at the neighbouring houses to ensure the validity of conducted measurement. When the Z_c value falls between 0.5 and 1Ω , a note should be taken to take preventive measure in the near future. In normal situation, the value of Z_c has to be lower than 0.5Ω to restrict the unsafe voltage rise in the faulty network. Table 7 summarises the findings of Z_c values for different types of earthing.

From the site measurement, it is observed that $Z_c > 0.5 \Omega$ mainly occurs in the areas where earthing is provided by water pipelines. After detailed investigation, it is found that sometimes the water agency replaces the metal pipelines by plastic water pipes without properly informing the network operators. In those places, the earth connection is broken/interrupted for the customer's installation and leaving it in unsafe situation. The remedy is to

Table 7 Measured circuit impedances with large values

Connection cable-earthing method	Measured Z_c , Ω	
	$Z_c > 0.5$, %	$Z_c > 1$, %
water pipelines	25.4	10.2
lead sheath of cable	4.8	1.6
separate earth conductor	2.4	1.6
litz of connection cable	0	0

place an earth conductor immediately and rebuild the earth return path. Sometimes it is also found that the connection terminal joints with the metal pipelines are not good enough or the connecting metal rod is too thin that causes higher resistance value. After detecting these types of defects, immediate repair action is done to lower the Z_c value below 0.5Ω .

If a connection cable uses lead sheath for earthing and has high Z_c , then the cable is immediately replaced by standard litz cables. Generally, earthing provided by a separate earth conductor should be reliable unless it is broken or missing (because of theft). If a high value of Z_c is found for this category, the continuity of earth conductor circuit is verified first and accordingly repair action is taken. In many cases, the customers do not notice the absence of earth conductor until a fatal incident (electric shock) occurs.

From the above analysis, it can be understood that for a TT system, customer himself needs to do proactive periodic control check of the earth electrode at his installation to ensure that it works properly. For TN system, a network operator is mainly responsible to guarantee that the earth return circuit impedance $Z_c < 0.5 \Omega$. If the Z_c value exceeds this limit, the utility is responsible to repair that part of network to bring it back into safe condition.

6 Proposal to optimise safety issues

From the discussion of this paper, it can be concluded that TN earthing system provides a safer earth route than TT configuration. In TT system, customer needs to install an earth electrode and should check its functionality regularly. On the other hand, in a TN system the network operator is responsible for the safe working of earthing network until the POC of the customer. When the customer's installation fulfils the standard guidelines of NEN 1010 (equivalent to IEC 60364), the network operator must guarantee that the installation is safe too against any external network fault. Therefore, the network operator should conduct periodic control checks at different network connection points to estimate the change of circuit impedance that might occur because of network modifications. In addition, proper remedy measures should be taken if the circuit impedance is found higher than 0.5Ω . The network operator should also conduct fault voltage measurement at different connection points to check that this value stays within the safe boundary limits. In the last years, the network simulation tools are used vastly to design and build all types of networks systematically, following standard design guidelines. The network analysis can also be used to check circuit impedance at different connection points of the network. The old networks that are designed decades ago, should be modernised gradually so that they satisfy the '5 s safety' rule or the maximum allowed fault voltage too. Earthing using the metal water pipelines should be forbidden totally. The main LV cable with earth shield and connection cable with litz wires should be used as standard cables and would be used for earthing. The shield wires and litz wires can be coupled with the neutral conductor at various terminal connection points. By this way, a double return path can be created for the earthing system. For this type of networks, the network operator can offer earthing point to all new LV customers to connect to their global earthing system. By this way, the customer can save his money too by avoiding the installation cost and regular inspection cost of his earth electrode and at the same time can have a safer earth connection for his installation.

7 References

- 1 The Dutch LV installation standard guidelines NEN 1010:2015 (similar to the International standard IEC 60364 series): 'Elektrische installaties voor laagspanning', (in Dutch)
- 2 Bhattacharyya, S., van Dael, T.: 'Risk management in a LV network on safety issues from asset management perspective'. Proc. of 23rd CIGRE Conf., 2015, paper no. 385, Lyon
- 3 Bhattacharyya, S.: 'Various internal investigation reports (of Endinet, now part of Enexis) on network's earthing and safety requirements', 2013–2016