

ENSURING PUBLIC SAFETY THROUGH PROPER EARTHING IN LOW VOLTAGE NETWORKS

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ABSTRACT

Every electrical supply network should provide a proper earthing system (grounding system) for its safe operation and for the safety of the 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 TT and 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 is provided by a dedicated earth conductor, combined network cable (PEN conductor), or via a separate earth electrode. When an earth return path is (for some reason) 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, first various types of LV network configurations will be discussed. Also, a practical monitoring based case study will be presented to analyse the diversity of earth resistance values for different LV network configurations. Also, guiding rules are given to define the 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 point of connection.

INTRODUCTION

The low voltage 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 & 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: TT and 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 66V or the fault has to be cleared within 5 second 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.

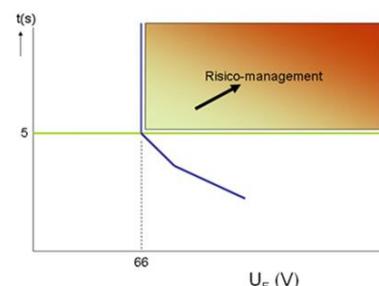


Fig. 1: Safety regulation in the LV networks of the Netherlands

In this paper, first various LV network configurations are discussed. A practical monitoring based case study is presented to analyze 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 optimize the safety needs at a customer's point of connection (POC).

LV NETWORK CONFIGURATIONS

Typical LV network configuration can be mainly of two types: 1) TT-earthed system (Terra-Terra, where the installation is earthed at customer's location by a separate earth electrode), 2) TN –earthed system (Terra-Neutral, 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.

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 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 middle '90s, a residual current device (RCD) is highly recommended by this standard to ensure additional safety of the customer's installation against direct and indirect shock hazards.

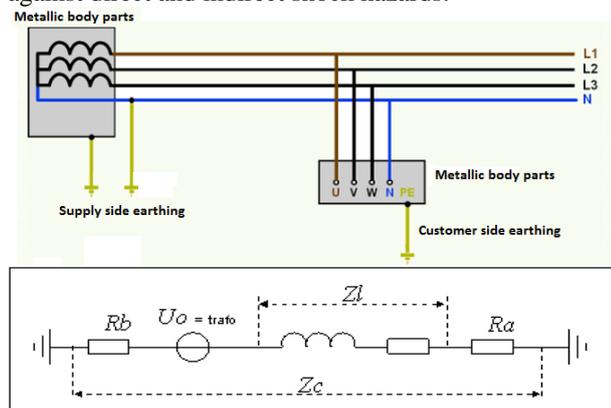


Fig 2: TT system and its equivalent impedance diagram

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

0,9 ohm as per NPR 5310 (2008) which is the practical Dutch installation guide for NEN 1010. The value of R_b is restricted to 0,4 ohm. In the next section of this paper, 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 sec (when potential bonding is used) for LV installation, while for the distribution group, it is restricted to 1 sec.

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-categorized in two groups: TN-C (combined system, where neutral & protective earth conductors are coupled together), and TN-S (separate earth system, in which neutral conductor and protective earth are separated). In TN-C 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 & disadvantages. In a TN-S system, the neutral & protective earth (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).

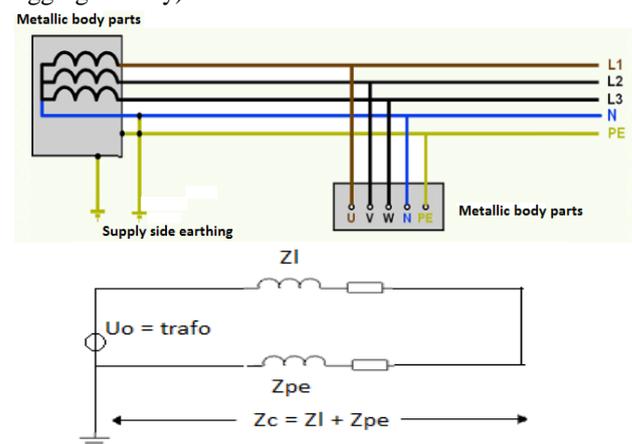


Fig 3: TN-S system & its equivalent impedance diagram

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 sec for LV installation. For distribution group, the maximum switching out time is restricted to 5 sec. 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.

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):

Table 1: Maximum circuit impedance in TT system

Protective device type	Maximum circuit impedance
Fuse type: gG- & 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.

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.

Table 2: Maximum values of circuit impedance in TT system

Installation capacity & protection type	Circuit impedance (Z_c) in ohm	Maximum value of earth electrode at customer's installation (R_a) in ohm	
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	*	*

From table 2 it is clear that TT-earthing configuration becomes unrealistic for larger capacity installations (>25A). 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 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 summarized 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.

Table 3: Maximum circuit impedance in TN system

Protective device type	Maximum circuit impedance
Fuse type: gG- & 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.

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

Table 4: Maximum values of circuit impedance in TN system

Protection type	Maximum circuit impedance (Z_c) in Ω				
	Installation capacity				
	16A	20A	25A	35A	40A
gG-& 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

From table 4, it can be seen that as the connection capacity of LV installation increases, the allowable limit for circuit impedance is decreasing. So, 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.,

DEVELOPMENTS IN SAFETY STANDARDS

In paper [2] the vision of the Dutch national regulator ACM ('Autoriteit Consument & Markt' in Dutch) about the safety requirements of public networks are discussed briefly. In this section, the latest developments are summarized. 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 $\leq 66V$ and/or fault clearance ≤ 5 sec), but are still performing perfectly. An unsafe 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 66V” or “5 second rule” principle where the fault current should be cleared by the main protective device present in the LV cable within 5 sec time or the fault voltage at different network parts should remain within the safe limit of 66V. For the existing networks, if these rules cannot be achieved, sufficient measures should be taken so that no parts 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.

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 criteria, 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 0,5 ohm 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 pipelines 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 litze 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: a) earthing of main cable, b) earthing of connection cable. In table 5, various combination of earthing methods that are used in this specific network are summarized.

Table 5: Various combination of earthing methods in main & connection cables

Earthing method used in main cable	Earthing method used in connection cable			
	Separate earth conductor	Litze of connection cable	Lead sheath of cable	Water pipeline
Separate earth conductor	Yes*	Yes*	Yes*	Yes
Neutral conductor	Yes	Yes*	-	-
Lead sheath of main cable	Yes	-	Yes	-
Water/ gas pipelines	Yes	-	Yes	Yes*

Note: * indicates that these are majority in numbers (minimum >1000).

From the internal asset database [3], it is found that >65% of the networks have separate earth conductor earthing system (TN-S), while around 15% have TN-C system where PEN conductor is used for earthing. Around 10% of the population have 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) are 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 are summarized.

Table 6: Distribution of earthing types for connection cables

Connection cable earthing method	Percentage of total
Separate earth conductor	49,60%
Litze of connection cable	29,90%
Lead sheath of cable	10,90%
Water pipelines	9,50%
Earth electrode	0,10%
Total	100%

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 $Z_c > 1$ ohm. Also 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 ohm and 1 ohm, 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 0,5 ohm to restrict the unsafe voltage rise in the faulty network. Table 7 summarises, the findings of Z_c values for different types of earthing.

Table 7: Measured circuit impedances with large values

Connection cable earthing method	Measured Z_c in ohm	
	$Z_c > 0,5$	$Z_c > 1$
Water pipelines	25,4%	10,2%
Lead sheath of cable	4,8%	1,6%
Separate earth conductor	2,4%	1,6%
Litze of connection cable	0%	0%

From the site measurement, it is observed that $Z_c > 0,5$ ohm 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 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 0,5 ohm.

If a connection cable uses lead sheath for earthing and has high Z_c , then the cable is immediately replaced by standard litze 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 don't 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 $Z_c < 0,5$ ohm. 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.

PROPOSAL TO OPTIMIZE 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 point of connection 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. Also, proper remedy measures should be taken if the circuit impedance is found higher than 0,5 ohm. 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 modernized gradually so that they satisfy the "5 sec 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 litze wires should be used as standard cables and would be used for earthing. The shield wires and litze 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.

REFERENCES

- [1] The Dutch LV installation standard guidelines NEN 1010:2015 (similar to the International standard IEC 60364 series) "*Elektrische installaties voor laagspanning*", (available in Dutch language only)
- [2] S. Bhattacharyya & T. van Dael, 2015, "Risk management in a LV network on safety issues from asset management perspective", *Proceedings of 23rd CIRED conference*, paper no. 385, Lyon.
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