# SAFETY: A VERY IMPORTANT FACTOR IN COST-OPTIMAL LOW-VOLTAGE DISTRIBUTION NETWORK DESIGN

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## SUMMARY

A new method is developed for low-voltage distribution network design. It enables the electricity distribution companies to calculate more accurately when engineering power distribution networks. The method is based on calculation of cost-optimal low-voltage cable diameters and correction for contact safety considerations. The paper introduces a phase-neutral-ground network model that includes all longitudinal and mutual impedances of the cable conductors. Contact safety of this network model is validated by means of measurements in practice. The available results of field experiments show that the results were always on the safe side.

## INTRODUCTION

Driven by both technological and economic factors, the electricity distribution companies in the Netherlands are forced to calculate more accurately when engineering new or renewed low-voltage power distribution networks. One of the technological factors is that many distribution companies are changing their policy from a TT-grounded system (Terra-Terra, where the installation is grounded at the client's location) to a TN-grounded distribution system (Terra-Neutral, where the electricity company provides the grounding as a service through the network). The electricity companies were used to ground the low-voltage terminals and the home electric systems of their customers at the metallic water conduits system. Since the water companies are using plastic instead of metal pipes nowadays, this grounding method is becoming obsolete. One solution is to apply grounding electrodes for each customer instead of grounding at the water system. An alternative way would be to have the distribution company provide the grounding together with the electric system. In the latter case the electricity company is responsible for proper grounding and calculations must be made in order to ensure safety at all times. Also, EMC problems in modern ITC equipment call for a TN method of grounding. A total earthing concept from high to low-voltage level including a description of field experiments is described by Cobben et al. (1) and by Van Waes et al. (2).

Another technological factor that drives the need for more accurate calculation is the growth of dispersed generating systems in the low-voltage system, such as combined heat and power and solar energy. This results in a reverse current path, which affects network operation and safety. Besides lower limits to voltage, developers now also need to reckon with upper limits to voltage. In addition, dispersed generation also occurs in the medium-voltage system, which greatly affects the voltage. These daily varying voltages have to be taken into account as well.

One important economic and political factor is the burden caused by liberalisation of the electricity market. The conventional engineering method was based on the use of certain engineering margins, incorporated in well-known rules of thumb. Decreasing these margins will result in decreasing the network investment costs. However, a low-investment network should not lead to higher operating costs, a poor voltage quality or unsafe situations for the connected customers. Due to this factor, the development of a new network will be increasingly difficult. This is why a new integral engineering method has been developed.

## METHOD

Typical for the situation in the Netherlands is that almost 100% of the low-voltage distribution systems consists of underground cables. The method of operating the distribution systems is historically determined. Networks are operated in radial as well as meshed configurations. Meshed networks are operated as open rings or as closed rings. Also historically determined is the great variety of cables and the methods of grounding.

Earlier developed software was oriented on specific items and on specific company needs, as described by Provoost (3). The deregulation leads to new nation-wide constraints imposed by the Regulator and new international standards. Company mergers and changes in the electricity sector initiated the need for a new tool that would be supported collectively. There was a collective desire for a new tool with a low acceptance threshold.

The method is based on expert knowledge rules that must be integrated. However, users in practice were non-experts who used to simple rules of thumb. They did not want to be confronted with lists of detailed input parameters and calculation procedures. Therefore, special demands for the new program concerned user-friendliness and recognisability. Participation of specialists and potential users from the electricity companies during development ensured good acceptance.

## GAIA

The method is called Gaia and consists of two major parts: calculation of cost-optimal cable diameters regarding the technical constraints and correction of the network for contact safety considerations. Besides, optimisation and safety calculations also on short and long-term voltage fluctuations (due to motor start and fluctuations in the medium-voltage system) and asymmetry are available in the method. The two major functions will be described in this chapter. The additional functions will be described briefly.

**Optimisation**

The aim of the optimisation is to develop a low-voltage distribution network at minimum lifetime costs. The procedure is based on a combined integer and real approach and is based on optimisation for economic operational management. In other words, the cheapest solution with respect to investment and electrical losses is sought for the estimated life time. A thicker cable requires a higher investment, but gives fewer losses, and vice versa (see Figure 1).

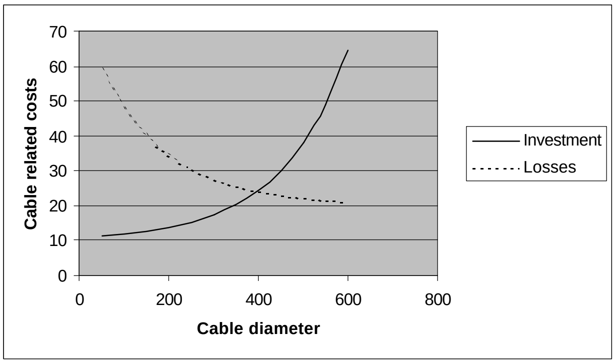


*Figure 1 Cable costs as a function of cable diameter*

The method ultimately selects the right cable with respect to load and voltage quality. The main variables in the process are cable diameters and transformer tap positions. These have to be determined in such a way that the cost-optimal configuration meets the technical constraints. The technical constraints are minimum and maximum voltage, maximum cable current and voltage fluctuations. The result strongly depends on the financial parameters, network lay-out, load size and growth rate and (dispersed) generation. In the network design process the planner first draws up the network. He enters the medium-voltage system with power supply, the MV/LV transformer stations and the low-voltage distribution networks. Using the graphical interface, the planner enters the nodes and the branches of specified lengths. The nodes may connect loads and generators. The branches may connect distributed loads, mostly of household types, and dispersed generation, e.g. solar power. The optimisation process selects the optimal cable types from a database of preferred types.

The financial parameters are electric energy price per kWh, electric power price per kW, estimated duration of losses (h/year) and net interest (percent/year). In the cost calculation all future costs will be converted to the net present value (NPV). For the planned period (e.g. 20-30 years) the growing losses (due to load growth) will be calculated using repeated load flow calculations. The total costs for one cable will be calculated as the investment cost ($C_i$) plus the sum over all future yearly loss costs ($C_v$), converted to present values. The total costs for the network ($C_t$) is the sum over all cable costs:

$$Ct = \sum_{cables}\left(Ci + \sum_{years}\left(Cv / annuity\right)\right)$$

To determine the network load and voltage, an AC model is used in the Newton Raphson load flow module. Besides the load, generators and motors can also be modelled. The growth of the load is taken into account in determining the total network load. Also, the simultaneity factor of the loads in a specific direction is taken into account. A correction is implemented on the Strand-Axelsson-based approach, such that the sum of loads is always correct. This correction for simultaneity is needed because e.g. the total of three groups of ten household loads numerically does not equal one group of thirty household loads.

The cost optimisation is an iterative process. First, the optimal cable diameters for a transformer medium tap position are chosen in an integer process. Subsequently, the technical constraints are checked. If they do not comply, larger diameters must be chosen. See Figure 2.

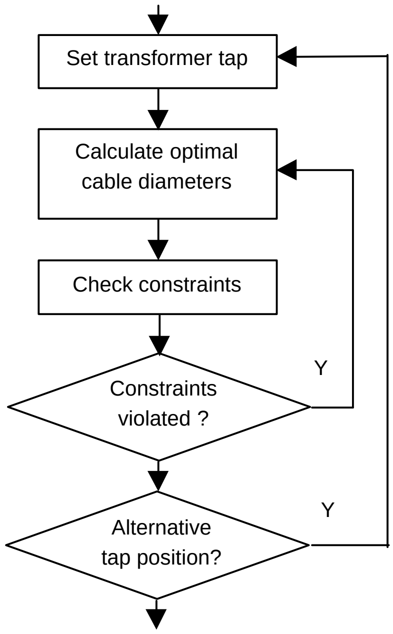


*Figure 2 Optimisation process*

Depending on the voltage distribution in the network, another transformer tap position may be chosen, possibly leading to a cheaper solution. For each tap position the optimisation of cable diameters must be executed. Figure 3 illustrates the voltage distribution in one direction for two solutions. There is no generation in this example. Solution A has a medium transformer tap position and a certain cable diameter. Solution B has a higher tap position and therefore smaller cable diameters. The voltage distribution in solution B has a larger voltage gradient. Solution B involves lower cable investment costs. As regards the cost calculation, evaluating the losses will determine whether A or B is the cheaper solution.

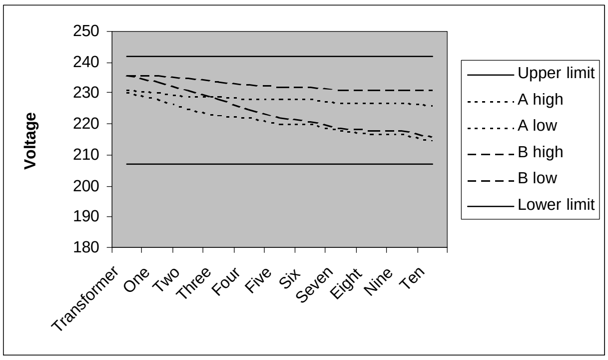


*Figure 3   Two possible solutions for one direction*

**contact safety**

In the event of a short circuit between a single-phase and the grounding of the electrical installation, a voltage difference originates between this ground conductor and the “far-off ground”. As a consequence of this, a current could run through the body of a person working with a grounded piece of equipment at that moment. The magnitude of this current determines the maximum time the fault may continue to exist. To combat the consequences of contact with this voltage, the connection must be turned off quickly enough. The connection between current running through the body and the allowable time is stipulated in the IEC 479-1 standard.

With grounding according to the TT system, the ground voltage during the fault – and with it the customer's safety – is almost totally determined by the impedance of the customer’s own grounding provisions. When there is a grounding error in the network cable, this customer experiences no voltage increase on his own grounding. The length of the network cable has no influence on the customer's safety here.

In a TN system the customer's grounding system is connected to the supplier's grounding system. Extra grounding electrodes may be installed. The neutral and ground in the supplier system are coupled where possible. When a phase-to-ground fault in the network cable occurs as in Figure 4, the neutral and ground lines will obtain a voltage with respect to the "far-off ground". In this case a person's body does experience a voltage through his grounding conductor. In order to avoid serious harm to persons, the fault has to be switched off in time. How quickly this must be done depends on the magnitude of the person's contact voltage. The voltage depends on the MV/LV transformer and the impedances of the low-voltage cable and the return path. The return path is determined by cable neutral and sheath and by additional grounding electrodes and ground resistance. In this context, the length of the network cable has a major influence on a person's safety. A longer cable will always lead to a longer cut-off time and thus to a longer exposure duration. For this reason, extra attention is given to the choice of the right network protection devices. The actual cut-off time depends on the fault current magnitude and the fuse characteristic. For a quick cut-off the total impedance has to be small. This influences the maximum cable length. For a low fault voltage the phase/return impedance ratio has to be large. If the network configuration does not meet the contact voltage requirements, additional measures can be taken for improvements, such as:

- enlarging the cable diameter for an impedance reduction and therefore a quicker cut-off time and
- extra grounding electrodes or extra ground connections for a neutral and ground network impedance reduction.

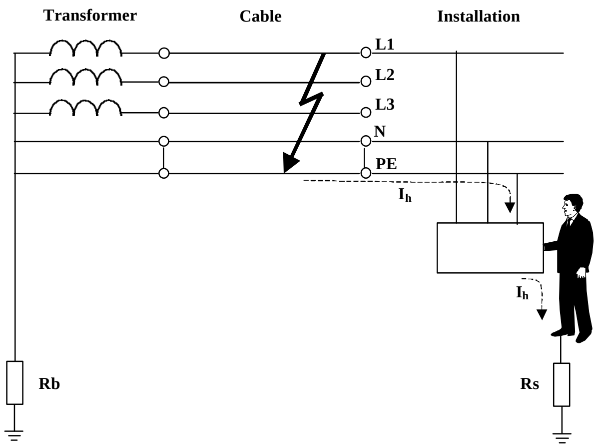


*Figure 4   Short circuit in a TN system*

Determining contact safety during short circuits in the low-voltage network with a TN grounding system is very complicated. In a proper calculation method not only the operating resistances and impedances play a role, but also the electromagnetic mutual coupling between the cable conductors. The safety for any human being is determined by the current-time curves according to IEC 479-1. Parameters are human body resistance (voltage-dependent), shoe resistance and the way of touching.

The voltage at the "touch" point is calculated using normal longitudinal impedances and mutual impedances for all conductive elements: three phases, neutral and sheath. For the calculation of a single-phase fault in the low-voltage system the mutual impedances may not be neglected. Therefore, a complete five-conductive-element system should be necessary, thus yielding a 25-element matrix for a cable.

The cable impedances are calculated from the cable construction, in which we distinguish types with round and sector-shaped conductors, see Figure 5. These are required for the calculation of the mutual impedances. In the left cross-section the mutual impedances are shown for two side-by-side conductors, for two opposite conductors and for a conductor and the sheath.

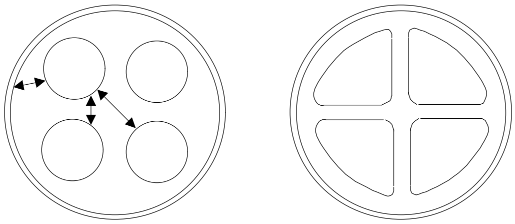

***Figure 5  Cables with round and sector-shaped conductors***

Considering the symmetrical construction of a cable, many mutual impedances in the cable model are equal. Therefore, we may write for the cable impedance system:

$$\begin{pmatrix} dU_{p1} \\ dU_{p2} \\ dU_{p3} \\ dU_{n} \\ dU_{s} \end{pmatrix} = \begin{bmatrix} Z_{phase} & Z_{pps} & Z_{ppo} & Z_{pns} & Z_{ps} \\ Z_{pps} & Z_{phase} & Z_{pps} & Z_{pno} & Z_{ps} \\ Z_{ppo} & Z_{pps} & Z_{phase} & Z_{pns} & Z_{ps} \\ Z_{pns} & Z_{pno} & Z_{pns} & Z_{n} & Z_{ns} \\ Z_{ps} & Z_{ps} & Z_{ps} & Z_{ns} & Z_{s} \end{bmatrix} \begin{pmatrix} I_{p1} \\ I_{p2} \\ I_{p3} \\ I_{n} \\ I_{s} \end{pmatrix}$$

Where:
p1..p3 : three phases
n : neutral
s : sheath
$Z_{phase}$ : phase conductor impedance
$Z_{pps}$: : mutual side-by-side phase conductors
$Z_{ppo}$: : mutual opposite phase conductors
$Z_n$ : neutral conductor impedance
$Z_{pns}$ : mutual side-by-side phase-neutral
$Z_{pno}$ : mutual opposite phase-neutral
$Z_s$ : conductive sheath impedance
$Z_{ps}$ : mutual phase-sheath
$Z_{ns}$ : mutual neutral-sheath

In the safety calculation only single-phase faults to ground have to be considered. As a result of this fault, the short circuit current will flow through the relative phase, neutral and ground only. The currents in the healthy phases have no effect on the result. Therefore, in the calculation a reduction of the system is made to a model consisting of Phase, Neutral and Ground only, so that a 3x3 matrix sufficiently describes the system of a low-voltage cable.

The cable impedances are calculated using the program EMTP/ATP Cable Constants for the round conductor type cables and a program using magnetic field calculations using the boundary element method for the sector-shaped conductor type cables. The results are stored in a cable database, so that the user will not be confronted with these theoretical parameters. The cable parameters can simply be updated, but this must be done by experts who are familiar with the cable parameters calculation method. At the moment all commonly occurring cables are modelled.

**Additional functionalities**

Two specific technical functions are added to the method for corrections in special cases: voltage dip and asymmetry calculations. The voltage dip due to a motor start may not exceed a defined value. A motor start is modelled as an extra single-phase-to-ground load that yields a new voltage profile, which can be compared to the nominal situation. The difference between the voltages in both situations is called the dip.

All distribution networks in the Netherlands are three-phase systems. Single-phase connections, e.g. household loads, are equally distributed over the cables. In the case of an asymmetrical load at the end of a long cable in a thinly populated area, the neutral may be shifted. The asymmetry in this case is calculated using the Phase-Neutral-Ground model, as described above.

**Result**

The method described above has been realised in the computer program Gaia. All calculations can be accessed by a graphical user interface. The program has a fast and simple one-line editor that can distinguish between the phase, neutral and grounding networks in layers. The user is supported in the construction and alteration of the network by component databases that contain all the technical data of the components. Consideration is given to the most important technical preconditions, such as the load-bearing capacity of the cables and transformers, voltage limits, motor start and the contact safety in the event of short circuits in the network. The interface and the calculation software run in Windows on a normal PC. All variables can be modified by the user, but a lock is built in for specific company-wide standards, e.g. voltage requirements, financial data and parameters for the safety calculation.

When it comes to human safety, a new network model and new cable data must definitely be validated for correctness by means of measurements in practice. The fault voltages and fault currents were measured by creating short circuits in an existing low-voltage network. The available results of field experiments show that the differences in contact voltages compared with the values determined using Gaia were less than 10%. The results from Gaia were always on the safe side.

Using this method, distribution companies have been able to realise substantial savings in cable investments. The program has been used by electricity companies in the Netherlands for about two years now. Depending on the engineering method before using Gaia, savings up to 10% of cable investment costs were realised. Also, when it comes to explanations to the management or the Regulator, the calculations show the economic and technical correctness of a low-voltage distribution network plan.

## GAIA IN PRACTICE

Introducing Gaia has led to interesting results. Some companies saved quite a lot of money using Gaia instead of rules of thumb. Gaia is used for the development of new networks and analysis of existing networks.

Introducing grounding by means of a TN system as a service to customers would initially lead to shorter network lengths than by means of a TT system with voltage constraints only. In TN systems the choice of the applied fuse needs more discipline. Because the network cable length influences the short circuit cut-off time, this gave an impulse to innovation of faster standard switching devices that will fit in the normal switchboard. These devices have a standard characteristic for normal overcurrents but are very fast at overcurrents due to faults. Thus, using TN grounding systems no longer has to lead to major constraints in network lengths. But care should be taken in choosing the right length of the customer connection cable, since this is still an important factor in the safety calculations. When introducing TN systems in existing networks, problems could occur when modelling older cables. Sometimes it is not known whether sheaths in the junctions are connected or not. Also, problems may occur when trying to model non-insulated copper wires in the ground and older mass-impregnated cables with their sheaths in contact with the soil.

The technical network requirements concern the cases with both power consumers (e.g. standard household loads) and dispersed generation (e.g. PV systems and combined heat and power). Also, medium-voltage fluctuations are taken into account. The requirements verification for upper and lower limits to voltage is treated in one single calculation. This simplifies the projection in modern network planning.

Thanks to the clear and open structure of the database concept, a conversion from and towards Geographical Information Systems (GIS) is quite easy. This means that in future systems lines can simply be drawn in the GIS, the network will be calculated in Gaia and the results such as cable types to be used will be stored in the GIS. Using more accurate information from the network may result in more accurate results. In the current model the calculations are made at two load points only: maximum load with minimum generation and minimum load with maximum generation. Future use of daily load curves and daily generation curves for different loads and different generations, e.g. on an hourly basis, should lead to more accuracy.

The calculation of networks for lower voltages requires quite a lot of reliable information. Often this information is not exactly known but the results of any calculation will be treated as the truth. Users should always use common sense and be aware of the inaccuracy of their results. Therefore, most of the electricity utilities in the Netherlands spend a lot of effort educating their workers to learn the basics of the program. Care should be taken to make sure that designer and project working staff respect the results of the calculation. This implies that the network has to be laid out exactly as it was calculated. Changes in the network, e.g. new customers or an extension of required power, always have to be updated in the model and have to be calculated first before being applied. The method owes its existence to discipline both in planning, laying and operating.

## CONCLUSIONS

A new method is developed for integral analysis and design of a low-voltage distribution network. The method is realised in a computer program called Gaia. The program offers functionality for cost-optimal network design.

Gaia has a completely new phase-neutral-ground network model, that includes all longitudinal and mutual impedances of the cable conductors. This enables the correct calculation of fault voltages and contact voltages in the network. Contact safety in the Gaia network model is validated by means of measurements in practice. The available results of field experiments show that the differences were less than 10%. The results from Gaia were always on the safe side.

The calculation method and the graphical user interface are developed in close co-operation with future users, in order to ensure a high degree of acceptance. Using this method, distribution companies have succeeded in substantial savings in cable investments. Depending on the engineering method before using Gaia, savings up to 10% of cable investment costs were realised.

Users should always use common sense and be aware of the inaccuracy of their results. Care should be taken to make sure that designer and project working staff respect the results of the calculation. The method owes its existence to discipline both in planning, laying and operating.

## LITERATURE


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