HOW TO ENSURE THE EFFICIENCY OF A GLOBAL EARTHING IN MV NETWORKS

D. Halkin, J. Hoeffelman
LABORELEC
Rodestrraat 125 B 1630 Belgium
E-mail: jean.hoeffelman@laborelec.be / didier.halkin@laborelec.be

Summary

A computer code together with a graphical method has been developed in order to calculate substation earth potential rise in MV networks
The simulation of an earth fault in more than 16 000 earth faults in the Belgian underground network, where the maximum fault current is generally limited to 2000 A, has shown that human safety was generally secured by active methods (working of the protections) without having recourse to additional measures (e.g. insulation).
It has also shown that the concept of global impedance was the most relevant parameter.

1. Introduction

Global earthing in MV underground networks consists in earthing and interconnecting all the cable sheaths (and any other metallic structures) in HV/MV and MV/LV substations in order to avoid dangerous voltages during phase to earth faults [1]. The efficiency of the global earthing is a function of different characteristics of the network:

- The topological configuration of the network (distances, number of substation interconnected, local earth resistances).
- The characteristics of the cables (diameter, impedance, presence of iron shield) and their insulation: jute envelop makes the sheath to be in good contact with the soil, while PVC ensures a perfect insulation.

In Belgium, global earthing is used in most MV networks with neutral earthed through an impedance that limits the fault current to 1, 2 or 4 kA.

In a first step, the contribution summarises how to synthesise and to use the above characteristics in order to detect substations where the Earth Potential Rise (EPR) exceeds a given threshold, and hence, how to check the global earthing efficiency.

In a second step, the results of the EPR calculation in about 16000 substations are summarised.

Finally, three further aspects of safety are discussed. They concern the reduction of potential rises by the use of pre-tripping, the expected insulation level of concrete poles and the estimation of admissible step voltage levels.

2. Global earthing

2.1 Inputs of the model

For the general case of earth fault in underground networks, a method has been developed in order to localise MV/LV substations where human safety is not automatically secured without additional passive measures.

The basic principle of the study lies on the fact that the global earth efficiency is mainly due to the cables and substations nearest to the substation where the fault occurs (about three sections upwards, and one downwards). This principle has led to an *equivalent network* consisting in a string of equidistant substations with the same earth resistance and one unique type of cable.

The following general characteristics of the actual network must be known:

- Admissible EPR:

The maximum allowed EPR can be determined using the IEC 479-1 curve (fig. 14) which gives the admissible current flowing through the human body. This EPR depends among other things on the duration of the stress and the additional resistance’s (shoes, etc.).

- Maximum fault current at the source (1, 2 or 4 kA);
- Type and section of the cables;
- Number of substations between the source and the studied substation:

The equivalent distance between the substations is the mean value of the three nearest sections upwards and the first downwards the short-circuit. This gives the fictive number of substations between the source and the substation under consideration (u.c.). The mean resistance is calculated using the same method.

- Distance between the source and the substation uc
- Downward substations:

Depending on some conditions[1] concerning the downward total length L of the network, the downward substations are considered as forming an infinite string of substations. Practically, this happens when:

[1] When the equivalent impedance of the downward network is less than 110 % of the impedance of an infinite string

$$\mathbf{L(m) \geq 2000 + 2.5\rho(\Omega m)} \qquad \text{Eq. 1}$$

for *jute cable* (with ρ the mean electrical soil resistivity). For these cables, the shield is considered as being in perfect contact with the soil.

$$\mathbf{L(m) \geq \frac{C}{n\ downward\ substations}} \qquad \text{Eq. 2}$$

for *cables with insulated sheath***,**
with C = 65 000 m. for ≤25 mm^2 cables,
80 000 m. for 95 mm^2 cables,
100 000 m. for ≥150 mm^2 cables.

When these conditions are fulfilled, the influence of the downward substations has to be taken into account. Otherwise, the substation can be considered as being in 'antenna' (last of the string).

- Soil resistivity:

When the network is based on paper-jute cables, the average electrical soil resistivity has to be known in order to modelise correctly the electrical contact between sheath and soil.

- Cable characteristics of the equivalent network:

Generally speaking, it is possible to modelise a network including different kinds of cables by an equivalent network with only one kind of cable. Therefore, the chosen cable should normally be of the same type of that one immediately upwards the substation uc. (with the condition that this latter has a length of the same order of magnitude as L calculated by eq. 1 or 2). In that case, the total equivalent length between the source and the substation u.c. is calculated in such a matter that the same fault current is got.

2.2 Mathematical model

The circuits including sheath and earth return are modelised by π quadripoles. The parameters of the quadripoles are calculated by using the line theory in order to correctly take into account the losses between sheath and earth in paper-jute networks.

For paper insulated cables, the non-linear characteristics of the iron sheaths are also taken into account. Indeed the presence of iron increases the shielding effectiveness of lead shields and hence decreases the EPR. An iterative calculation process is used: The p.u. length impedance of the circuit sheath-earth return depends on the vectorial sum of the conductor- and sheath currents, which, in turn, depends on the p.u. length impedance.

2.3 Results

The maximum admissible earth resistance of the substation u.c. can be read on a set of curves, in function of the equivalent distance between source and substation. Each curve on the figure has as parameter the number of intermediary substations (including source and substation u.c. ie: 2, 4, 6, 8, 10, 14, 22 or 30 substations).

The results of the simulations show that substations close to the source will rarely cause problem for human safety as the fault current returns to the source mainly via the sheath.

On the other hand, due to the limited fault current, substations laying far from the source will neither cause any problem. This conclusion is even enhanced with paper-jute cables, where the losses directly depend on the length of the cables.

As an example, Figure 1 shows the local earth resistance (paper-jute Cu 25^2 cables, network voltage 12 kV) which leads to an EPR of 800 V during a fault in a substation in antenna, the soil resistivity being equal to 120 Ωm and the fault current being limited to 2000 A at the source.

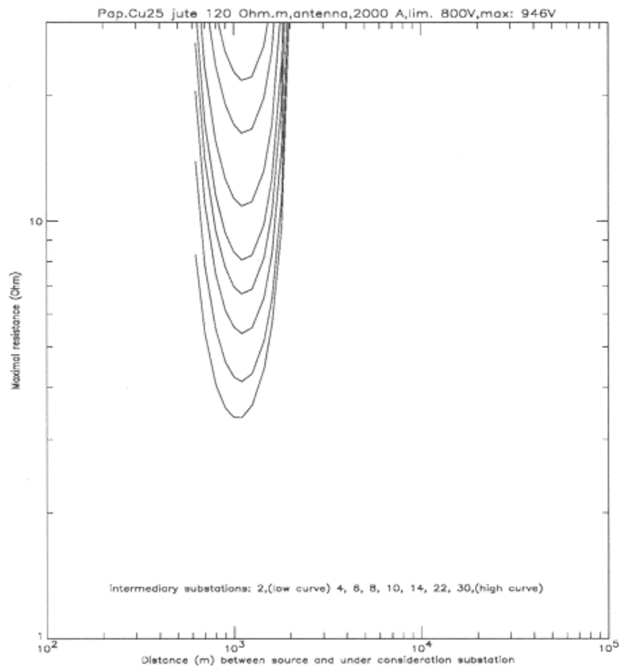

Figure 1**: Maximum allowed earth resistance in a MV underground network (Paper jute Cu 25^2)**

Figure 2 shows the resistance (paper-PVC Cu 150^2 cables, network voltage: 12 kV) which leads to an EPR of 600 V during a fault in an intermediary substation, the fault current being limited to 1000 A at the source.
The "max" figure given above the graphics are the maximum EPR reached in the substation next to the source (two intermediary substations) when the earth resistance reaches 30 Ω.

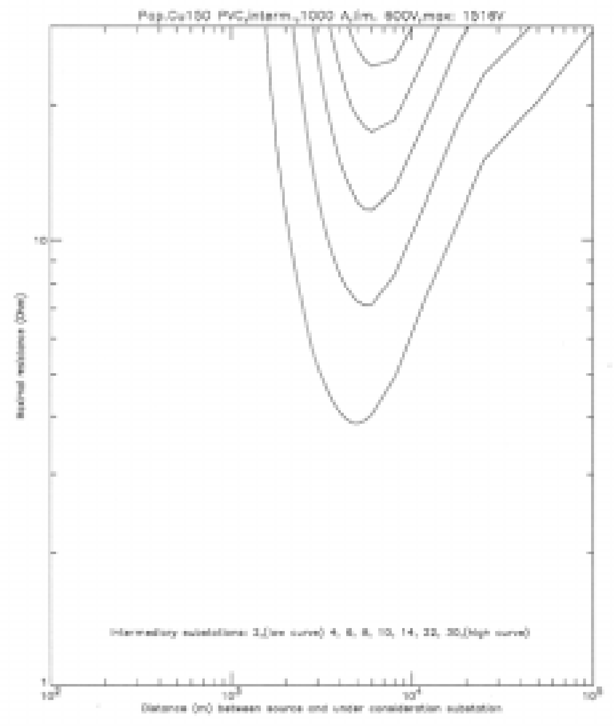

Figure 2**: Maximum allowed earth resistance in a MV underground network (Paper PVC Cu 150^2)**

2.4 Conclusions

A comprehensive graphical method for determining the maximum admissible earth resistance of MV substations has been presented.
The study shows that some parameters are very deterministic for assessing the efficiency of global earthing ; mainly:

- The earth resistance of the substations;
- The distance source-substation u.c.
- The number of substations uprwards and downwards;
- The type of cable (jute or PVC) + soil resistivity;
- The maximum fault current at the source.

If the substation earth resistance is higher than the maximum resistance found with this method, different techniques can be used to ensure human safety. These are among other things:

- To increase the admissible voltage by enhancing the additional resistances in the body-earth circuit (tarmac, stones, gravel);
- To decrease the maximum fault current;
- To decrease the substation earth resistances;
- To reduce the touch voltages by extending the earth network (equipotential surface).

The use of drain cables (underground earth cables) in PVC insulated new networks is also a good solution.

3. EPR calculations

The EPR has been calculated in about 16.000 substations of the MV network. This study had four targets:

- To confirm the results of the above explained method;
- To evaluate the amount of safe substations;
- To study the rule of the *global earth impedance*, i.e. the local earth impedance of a substation measured without disconnecting the cable sheaths;
- To make a correlation between the global impedance, the fault current and the EPR.

3.1 Data

The electrical characteristics (cables lengths and types) of a feeder fed by a given HV/MV transformer are taken from the network data files. This makes it possible – and necessary – to modelise correctly some parameters that could not fully be taken into account in the above-explained method (see § 2).

These are:

- The earth loops due to the metallic cable screens;
- The loops in the feeders (multifeeding);
- The correct influence of all the nearby substations;
- The mix-up of insulated cables (PRC) and paper-lead cables, with different sections and lengths.

A value of 10 Ω has been chosen a priori for the substation earth resistance. As written in the conclusions, this value is not that important. This is due to the fact that the *global earth impedance* plays the most important part, and not the *local resistance.*

When a network configuration (connection of different busbars, new substation, new cable, etc.) has to be changed, new calculations can be automatically done in order to adapt the results.

3.2 Expected results

The expected results are, on the one hand, the potential rise in each substation (three cases are investigated, depending of the maximum limit for the fault current :1, 2 or 4 kA); and on the other hand, the value of the global impedance (which can be measured) in each substation. The main difference between the calculation of the EPR and that of the global earth impedance concerns the current injecting place: In the first case it is the feeding point (HV/MV substation), in the second case the MV/LV substation itself. This is mathematically represented in terms of mutual impedances between the involved loops.

The global impedance is calculated at 50 Hz but also at 110 Hz because most measurements are made at this second frequency.

3.3 Calculations

3.3.1 Loops in the network

For a given network with n different cables, the path followed by the fault current from the source to any substation has first to be calculated.

Taking into account the interconnections between the substations, the whole network is followed by a 'cursor', cable per cable from the source. For each handled cable, a stack is completed. If a cable already handled is found, the cursor has to find the next connected cable or to go back, and so on till the cursor reaches the source again. Each time a new substation is reached, the content of the stack shows the fault current path to the source. If the substation has already been found, there is a *feeding loop*. This loop is memorised and the cursor goes one step back.

The second step consists in finding the *earth loops* made by the cable sheaths. A similar method is used, but the conditions to go from a cable to the next one are less strict: no rule exists in terms of connections between different busbars in a substation.

From this work, n_{e_lp} *earth loops* and n_{flt_lp} *feeding loops* (different for each substation) are derived.

3.3.2 Resolution of the system

For each substation, a complex system of $n+n_{e\_lp}+n_{flt\_lp}$ equations has to be solved. Sometimes, the size of this system can exceed 10^3 elements. In order to reduce the resolution time, an acceleration method for quasi tridiagonal systems has been developed. This method is not explained in this article.

The influence of the non linear iron shields and that of the contact between lead sheaths and soil is taken into account. The used method has been explained at CIRED 97, (Session 2, Question 5).

From these calculations, the earth potential rise of each substation and its global impedance are deduced.

3.4 Results

In most cases, the substations are safe in terms of step and touch voltages. In some cases (1%), safety is not secured when considering the maximum fault duration (1 s). This occurs mainly with PRC cables. Fortunately, most of the concerned substations are located at the end of an antenna, where the fault current is eliminated in less than 0.5 s.

The great safety of the MV networks that have been examined is mostly due to the continuous contact between lead sheath and soil. Only a small part of the networks is based on PRC cables.

Additional safety measures (such as insulation) have only to be taken in a few substations. A general reduction of the maximum fault current from 2 kA to 1 kA is certainly not mandatory.

On the other hand, limitation to 1 kA should be recommended in a completely new network with only PRC cables.

3.5 Correlations

When an automatic calculation method cannot be applied (e.g. no data file), it remains possible to find a very good approximation of the EPR when the fault current I and the global earth impedance Z (50 Hz or 110 Hz) are known. The best correlation between these three variables has been calculated for different networks. It leads to the following expression:

$$\boldsymbol{EPR \equiv U = a * Z^{b} * I}$$

In the figures below (with I_{max} = 2 kA), the values of U / I are presented in function of Z.

In order to get a correct correlation for high EPR, only the substations where the EPR is > 400 V have been represented. The standard deviation S of the error in terms of EPR has been minimalised. A comparison of the results with I_{max} equal to 1 and 2 kA shows that the same values for a and b can be kept when the global earth impedance is measured at 50 Hz. Other values, however, have to be chosen for 110 Hz measurements.

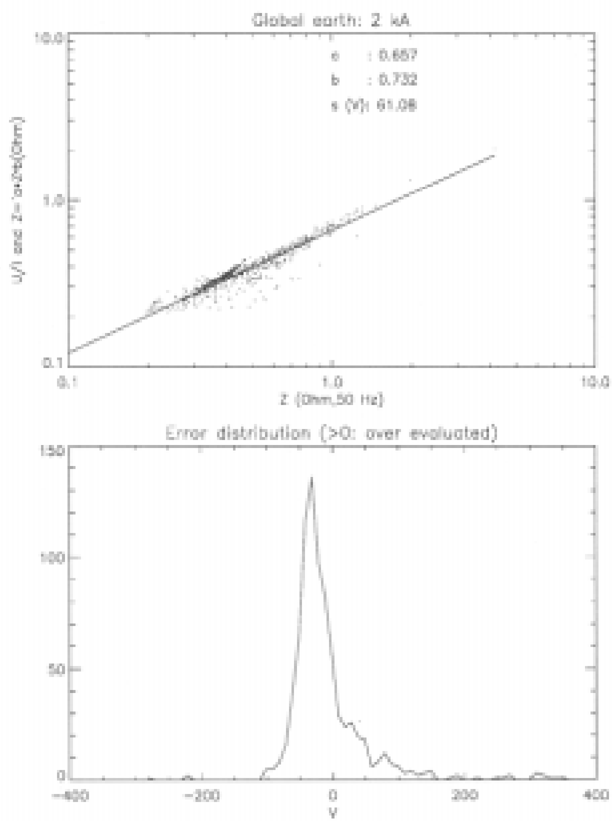

Figure 3a**: Correlations between U/I and Z (at 50 Hz)**

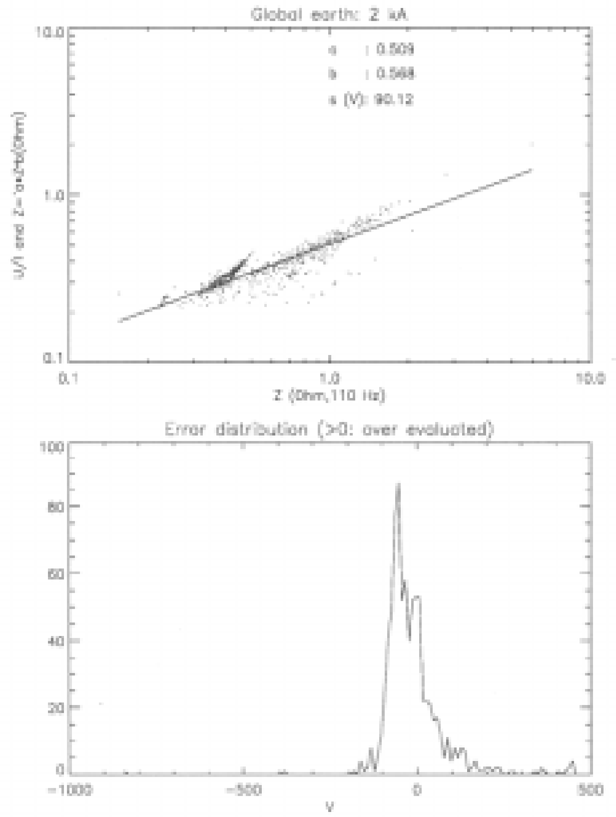

Figure 4b**: Correlations between U/I and Z (at 110 Hz)**

A good approximation of the fault current can be calculated by considering only the source impedance (limitation to 1 or 2 kA), the impedance of the feeding conductor and that of the screens (return path). Parallel cable returns and earth returns can be neglected.

4. Conclusions

A computer code has been developed in order to calculate the the Earth Potential Rise of MV substations under fault condition, taking into account all the electrical parameters of the network .This method has been applied to more than 16000 substations of the belgian underground network

The relatively low EPR's found has shown that the networks remains generally safe when the maximum fault current is limited to 2 kA, but that new PRC networks should be fed by a source with lower fault current limitation or with additional earth cables.

5. Other considerations

5.1 Pretripping

One method to reduce potential rises consists in quickly reducing the short-circuit current from e.g.2 kA to 1 kA. This can be done by applying *pre-tripping* (Figure 4).

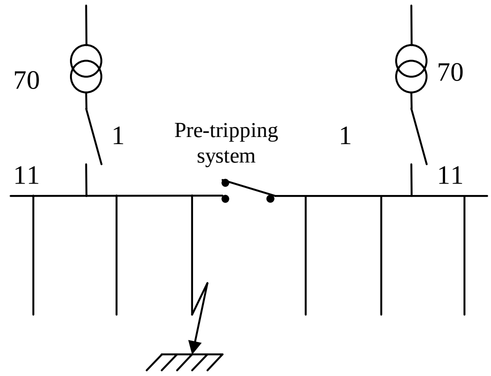

Figure 5: **Pre-tripping in MV networks**

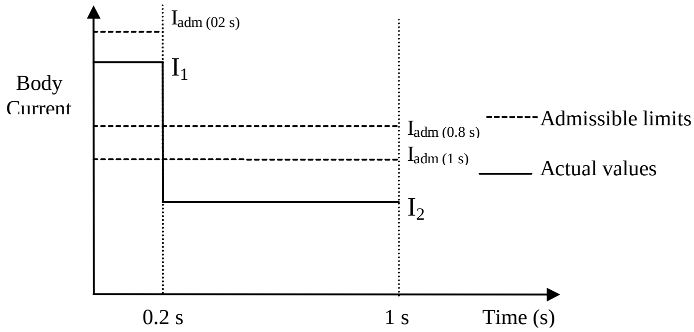

Figure 6: **Actual and admissible body currents during a fault**

The following question however needs an answer:
How can IEC 479-1 curve be applied in order to determine if two consecutive stresses (I_1 and I_2 , see Figure 5) are admissible. when it is assumed that I_1 is admissible ($<I_{adm\ (0.2\ s)}$) during 0.2 s and that I_2 is admissible during 1 s ($< I_{adm\ (1\ s)}$) ?

On basis of the work done by Prof. Biegelmeier [2] of which a summary has been made (*12/1998*) by CIGRE WG 36.02., the following statement can be made:

If a first high stress lasting less than one third of the heart beat (< 0.2 s) does not lead to fibrillation, it can only lead to a first premature beat, just like a constant stress lasting for the total beating period. Hence, the following stress will not produce any new premature heart beat if the level remains lower than the admissible limits given for the whole period.

Another statement is that, when a first low stress (with no fibrillation) leads to premature beats, a possible higher stress following can cause fibrillation even with a lower level than that given by the IEC safety curve. This is because the fibrillation threshold of the second premature beat is lower than that of the first one.

As a conclusion, it seems that the consequence of a first high stress (of which the level is lower than the fibrillation threshold) with a duration shorter than 0.2 s followed by another lower stress (level lower than the admissible level for the <u>*whole*</u> stress duration) can be neglected.

5.2 Insulation by concrete

In aerial networks, where global earthing does not exist, the MV/LV transformer put on concrete poles has to be locally earthed. If the earthing conductor is embedded in the pole, the concrete should increase the additional resistances of the body-earth circuit and, hence, increase the safety.
Unfortunately, the resistivity of concrete can change from less than 40 Ωm to more than 1000 Ωm depending of the degree of humidity and porosity. Therefore it doesn't seem to be advisable to take any insulation effect into account when dealing with concrete.

5.3 Step voltages

The present study concerns mainly the problems of touch voltages. In some cases, the extension of the earth network outside the substation (in order to decrease the touch voltages) may increase the risk of step voltages. Moreover, step voltages can be found everywhere and not only in the direct vicinity of the HV installation.

Fortunately, the admissible step voltages are far higher than the touch voltages. This difference is mainly due to the following two factors:

1. As safety is related to the current flowing in the heart region, a heart-current factor F is introduced depending on the path followed by the current. When comparing touch and step voltages, this factor equals 0.45 (currents due to step voltages are safer).

2. In terms of touch voltages, the additional resistances due to the shoes are in parallel, whereas for step voltages, these resistances are in serie, as far as there is no coupling between them [3]. With an equal additional resistance for each shoe, a factor 4 has to be introduced between both cases.

REFERENCES

[1] CENELEC prHD 637 S1
Power installations exceeding 1 kV a.c.
Final draft April 1998

[2] G. Biegelmeier, W.R. Lee
New considerations on the threshold of ventricular fibrillation for a.c. shocks at 50-60 Hz
IEE Proc., Vol 127 n°2, 3/1980

[3] ANSI/IEE Standard 80-1986 *Guide for Safety, ch. 6.2, p 46*