Proceedings of the 2006 IASME/WSEAS International Conference on Energy & Environmental Systems, Chalkida, Greece, May 8-10, 2006 (pp207-212)

# Proximity effect on bare buried conductors connecting together MV/LV substations' earth electrodes

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*Abstract:* - A model to study the interconnection of MV/LV substations' earth electrodes through bare buried conductors is presented. The model is based on the transmission line's equations for buried conductors and on the multiport representation of the MV network; moreover it takes into account the proximity effect. The model can be used to study the rise of dangerous voltages inside urban areas during earth faults in order to identify a Global Earthing System. An application example allows to demonstrate the benefits of the use of buried conductor like interconnection elements.

*Key-Words:* - Proximity Effect, Bare Buried Conductors, Global Earthing Systems, Electrical Safety.

## 1 Introduction

Urban areas are, generally, characterized by earthing systems connected together so as to form an unique extended earthing system. An interconnected earthing system can form a quasi-equipotential surface below the urban area, in which no dangerous voltages exist. In this case it can be defined "global earthing system" (GES in the following) [1].

At a normative level, today, no universal criteria have been defined to identify a GES, but, because of the enormous importance of GES for electrical safety, several Distribution Companies and research societies have given their contributions to this issue [2-3].

A possible way to identify a GES is the analytical study of the behavior of the interconnected MV earthing systems during every possible fault condition, using specific software based on suitable mathematical models. IEC Standard 60909-3 [4] proposes some simple models for the study of earth fault in interconnected earthing systems within HV networks. Nevertheless, because of the great differences between HV networks, having mesh structure and directly earthed neutral, and MV networks, having radial structure and isolated or resonant earthed neutral, these methods are not suitable for MV networks and in several practical cases lead to high errors.

In recent years, the authors carried out an analysis methodology for the study of interconnected earthing systems within MV networks. The methodology is based on the division of the MV network and of the related extended earthing system that it includes in subsystems whose behavior is described by matrix equations. The methodology has been applied with satisfactory results both to isolated neutral [5] and to resonant earthed neutral networks [6], in the case of interconnection of the earth electrodes of the MV/LV substations done by MV cables' metal sheaths.

The same methodology has been adopted to study earthing systems interconnected by bare buried conductors [7]. In this case, in order to simplify the mathematical models, the proximity effect between the buried conductors and the earth electrodes of the substations have been neglected.

As it will be shown in the following, such a simplifying hypothesis leads to acceptable errors as earth bulk resistivity ρ is not higher than few hundreds Ω·m.

However, in several practical cases, extended earthing systems develop within higher resistivity soils. This situation is typical, for example, of little volcanic Mediterranean islands. In these cases the proximity effect is not negligible and the presence of the phenomenon considerably affects the results of the calculations.

The analytical identification of GES, must be as more accurate as possible to be significant and so the utilized models must take into account also the proximity effect when necessary.

Technical literature presents many papers dealing with the issue of the proximity effects on bare buried conductors. In [8], Machczyński proposes an analytical-numerical method to take into account the proximity effect based on the transmission line's equations.

The paper, fusing the methodology defined in [5-7] and a simplified version of the method illustrated in [8], intends to complete the study of the interconnected earthing systems within MV networks giving a further contribution to the issue of the identification of GES.

Firstly the paper deals with the definition of a lumped parameters model for bare buried conductor, starting from and elaborating the method proposed in [7]. Subsequently the model obtained is included in the model of a MV line and then of the whole MV power system (Fig. 1) defined in [5-6].

Finally a discussion above the results of the simulations done using software based on the defined model, is presented.

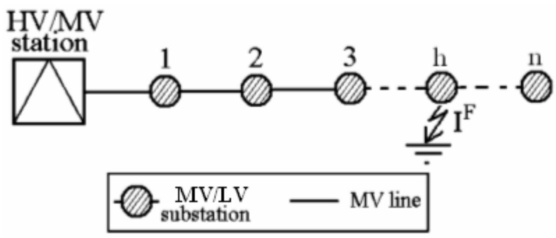


Fig. 1. Schematic representation of the system.

## 2 Model of the bare buried conductor

In Fig. 2 is represented a bare buried conductor, long L, connecting the earth electrodes of two MV/LV substations.

The phase conductors of the MV line induce in the buried conductor a voltage drop $E_C$ given by:

$$\overline{E}_C = j\frac{\omega\mu_o}{2\pi}\cdot\ln\frac{\sqrt{2H_E}}{D_{c1}}\cdot\overline{I}^{c1} + j\frac{\omega\mu_o}{2\pi}\cdot\ln\frac{\sqrt{2H_E}}{D_{c2}}\cdot\overline{I}^{c2} + + j\frac{\omega\mu_o}{2\pi}\cdot\ln\frac{\sqrt{2H_E}}{D_{c3}}\cdot\overline{I}^{c3} \qquad (1)$$

where $I^{ci}$ is the current flowing through the $i^{th}$ conductor of the line, $D_{ci}$ is the distance between the buried conductor and the $i^{th}$ conductor, and $H_E$ is given as function of the frequency f and of the earth resistivity ρ by:

$$H_E = 330\cdot\sqrt{\rho / f} \qquad (2)$$

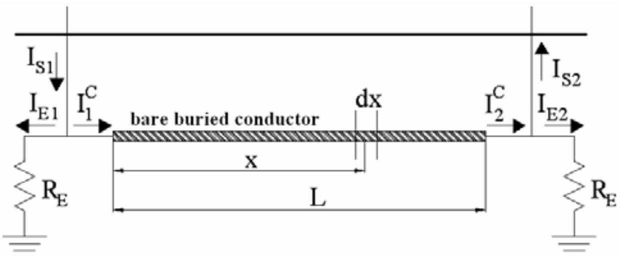


Fig. 2. Bare buried conductor connecting together the earthing systems of two MV/LV substations.

An infinitesimal part of the system, including both the phase conductors and the buried conductor, is represented in Fig. 3.

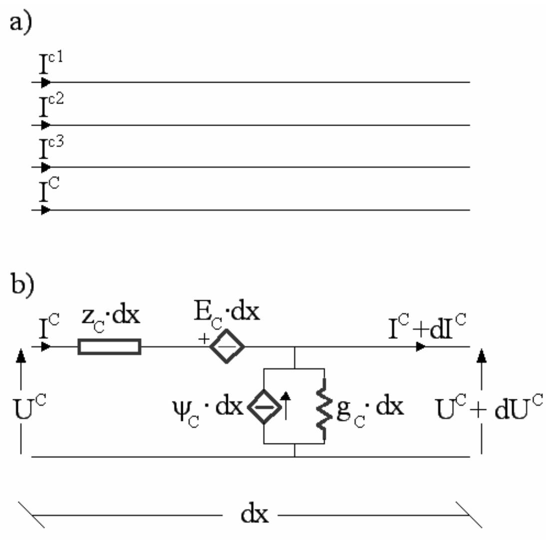


Fig. 3. a) Conductors of the system (c1, c2, c3: phase conductors; C: bare buried conductor) – b) Equivalent circuit of an infinitesimal part of the buried conductor.

In Fig.3, $z_C$ and $g_C$ are, respectively, the series impedance and the shunt admittance per unit length of the buried conductor and $\psi_C\cdot dx$ is a current generator representing the proximity effect whose value is given by:

$$\overline{\psi}_C = \frac{\rho\cdot g_C}{\pi\cdot D_1}\cdot\arcsin\left(1+\frac{2\cdot x}{D_1}\right)\cdot\overline{I}_{E1} + + \frac{\rho\cdot g_C}{\pi\cdot D_2}\cdot\arcsin\left(1+\frac{2\cdot(L-x)}{D_2}\right)\cdot\overline{I}_{E2} \qquad (3)$$

where $I_{E1}$ and $I_{E2}$ are the current flowing through the earth electrodes of the substations connected to the conductor and $D_1$ and $D_2$ are the equivalent diameters of the earth electrodes. For the circuit in Fig.3, the following equations are written:

$$\begin{aligned} d\overline{I}^C &= -g_C\cdot\overline{U}^C\cdot dx + \overline{\psi}_C\cdot dx \\ d\overline{U}^C &= -z_C\cdot\overline{I}^C\cdot dx - \overline{E}_C\cdot dx \end{aligned} \qquad (4)$$

From (4) the following equations are obtained:

$$\begin{aligned} &\frac{d^2}{dx^2}\overline{I}^C - \dot{z}_C\cdot g_C\cdot\overline{I}^C - g_C\cdot\overline{E}_C - \frac{d}{dx}\overline{\psi}_C = 0 \\ &\frac{d^2}{dx^2}\overline{U}^C - \dot{z}_C\cdot g_C\cdot\overline{U}^C + \dot{z}_C\cdot\overline{\psi}_C = 0 \end{aligned} \qquad (5)$$

whose solutions are:

$$\overline{I}^{C}(x)=\frac{\overline{I}_1\cdot Sh\left[\dot{\alpha}\cdot(L-x)\right]}{Sh(\dot{\alpha}\cdot L)}+\frac{\overline{I}_2\cdot Sh(\dot{\alpha}\cdot x)}{Sh(\dot{\alpha}\cdot L)}+$$
$$+\frac{\overline{E}_C}{\dot{z}_C}\cdot\frac{Sh(\dot{\alpha}\cdot x)+Sh\left[\dot{\alpha}\cdot(L-x)\right]-Sh(\dot{\alpha}\cdot L)}{Sh(\dot{\alpha}\cdot L)}+ \tag{6}$$
$$+2\cdot\left[\overline{\Phi}(x)-\overline{\Phi}(L)\right]\cdot Sh(\dot{\alpha}\cdot x)$$

$$\overline{U}^{C}(x)=\frac{\dot{z}_o\cdot\overline{I}_1\cdot Ch\left[\dot{\alpha}\cdot(L-x)\right]}{Sh(\dot{\alpha}\cdot L)}-\frac{\dot{z}_o\cdot\overline{I}_2\cdot Ch(\dot{\alpha}\cdot x)}{Sh(\dot{\alpha}\cdot L)}+$$
$$+\dot{z}_o\cdot\frac{\overline{E}_C}{\dot{z}_C}\cdot\frac{Ch\left[\dot{\alpha}\cdot(L-x)\right]-Ch(\dot{\alpha}\cdot x)}{Sh(\dot{\alpha}\cdot L)}+ \tag{7}$$
$$+2\cdot\dot{z}_o\cdot\left[\overline{\Phi}(L)\cdot Ch(\dot{\alpha}\cdot x)+\overline{\Phi}'(x)\cdot Sh(\dot{\alpha}\cdot x)\right]$$

where:

$$\dot{\alpha}=\sqrt{\dot{z}_C\cdot g_C}\qquad \dot{z}_o=\sqrt{\dot{z}_C/g_C}$$
$$\overline{\Phi}(x)=\frac{\overline{\Phi}_1(x)+\overline{\Phi}_2(x)}{2\cdot Sh(\dot{\alpha}\cdot x)}\qquad \overline{\Phi}'(x)=\frac{\overline{\Phi}_1(x)-\overline{\Phi}_2(x)}{2\cdot Sh(\dot{\alpha}\cdot x)}$$
$$\overline{\Phi}_1(x)=\frac{1}{2}\cdot e^{-\dot{\alpha}\cdot x}\cdot\int_0^x\overline{\Psi}_C(x)\cdot e^{\dot{\alpha}\cdot x}\cdot dx \tag{8}$$
$$\overline{\Phi}_2(x)=\frac{1}{2}\cdot e^{\dot{\alpha}\cdot x}\cdot\int_0^x\overline{\Psi}_C(x)\cdot e^{-\dot{\alpha}\cdot x}\cdot dx$$

and Ch and Sh, are the hyperbolic cosine and sine functions, respectively.

The buried conductor can be represented by a pi-circuit whose parameters can be obtained by elaborating equations (6) and (7). The equivalent circuit is shown in Fig.4.

In Fig.4 is:

$$\dot{Z}_{CL}=2\cdot\dot{z}_o\cdot\frac{Ch(\dot{\alpha}\cdot L)-1}{Sh(\dot{\alpha}\cdot L)}\qquad \overline{E}_{CL}=\dot{Z}_{CL}\cdot\frac{\overline{E}_C}{\dot{z}_C}$$
$$R_C=\frac{\dot{z}_o\cdot\left[1+Ch(\dot{\alpha}\cdot L)\right]}{Sh(\dot{\alpha}\cdot L)}$$
$$\overline{\Psi}_{C1}=\overline{\Psi}_C^*-(\dot{\beta}+1)\cdot\overline{I}_C^{\Psi}\qquad \overline{\Psi}_{C2}=\overline{\Psi}_C^*+(\dot{\beta}+1)\cdot\overline{I}_C^{\Psi}$$
$$\overline{\Psi}_C^*=\overline{\Phi}(L)\cdot Sh(\dot{\alpha}\cdot L)+\overline{\Phi}'(L)\cdot\frac{Sh(\dot{\alpha}\cdot L)}{1+Ch(\dot{\alpha}\cdot L)} \tag{9}$$
$$\dot{\beta}=\frac{Ch(\dot{\alpha}\cdot L)-1}{Ch(\dot{\alpha}\cdot L)+1}$$
$$\overline{I}_C^{\Psi}=-\frac{\overline{\Phi}_1(L)+\overline{\Phi}_2(L)}{2}+\frac{\overline{\Phi}_1(L)-\overline{\Phi}_2(L)}{1-Ch(\dot{\alpha}\cdot L)}$$

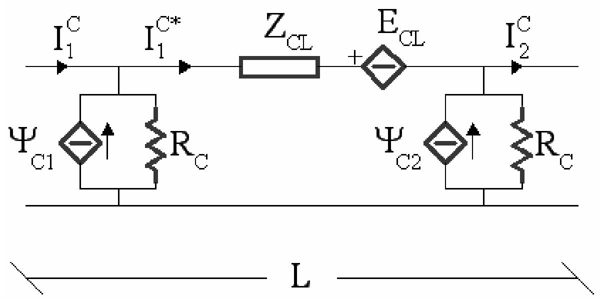


Fig. 4. Equivalent circuit model of a bare buried conductor connecting together the earthing systems of two MV/LV substations.

## 3 Model of the system

In order to study the system made by the MV network and by the interconnected earth electrodes, the methodology proposed in [5] is used.

According to [5] each MV line is made by a cascade of multiports representing the sections of the line between two MV/LV substations.

Each section is made by three phase conductors, the metallic elements interconnecting the earth electrodes, and part of the earth resistances of the substations. Indeed substations earth electrodes resistances are split into two identical resistances and each part is included in the circuit model of one of the two sections of the MV line connected to the substation.

The equivalent circuit model of the bare buried conductor defined in Fig.4 is included in the multiport representing the generic i[th] section of the faulted MV line (Fig.5).

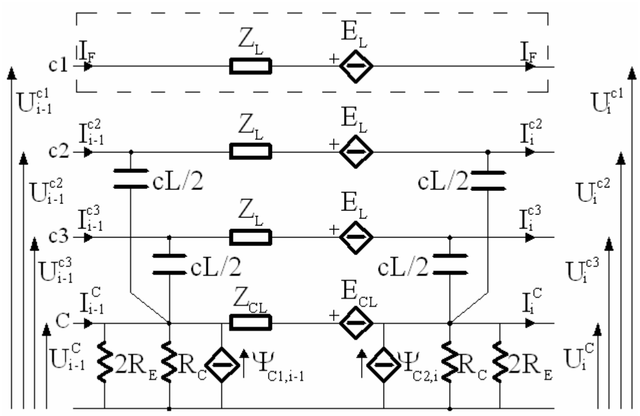


Fig. 5. Equivalent circuit model of a section of the MV line between two substations.

In Fig.5, c1 is assumed to be the faulted phase conductor, $I_F$ indicates the fault current, $c\cdot L$ the mutual capacitance between the generic phase conductor and the bare buried conductor, $Z_L$ the impedance of the generic phase conductor evaluated according to Carson's theory, $E_L$ a current-controlled voltage generator representing the effect of the mutual coupling between the generic phase conductor and the buried conductor, and subscripts “i-1” and “i” indicate, respectively, the input and output voltages and currents of the section.

According to the model explained in [5], are distinguished section of MV line above the fault location and sections below the fault location. In the model, below the fault location, the faulted phase conductor c1 is not considered. Moreover, if the circuit model in Fig.5 represents the section ending at the fault location, a short-circuit connection must be inserted between the faulted phase conductor and the buried conductor.

In Fig.6 is shown the circuit model of the HV/MV station.

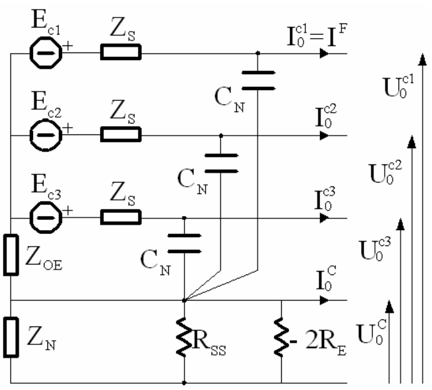


Fig. 6. Equivalent circuit model of the HV/MV station.

In Fig.6, $Z_{OE}$ is the impedance connecting the neutral of the MV network with the earthing system of the station, $R_{SS}$ is the earth resistance of the station, $Z_N$ is the equivalent earth impedance of the rest of the interconnected earthing system, $C_N$ is the equivalent capacitance of the MV network excluded the faulted line, $Z_S$ is the internal impedance of the source and $E_{ci}$ is the equivalent phase source.

For each part of the system, writing in a matrix form the equations obtained applying Kirchhoff's laws, it's possible to obtain an input-output relation of the following type:

$$\begin{bmatrix} \overline{U}_{i-1}^{c1} \\ \overline{U}_{i-1}^{c2} \\ \overline{U}_{i-1}^{c3} \\ \overline{U}_{i-1}^{C} \\ \overline{I}_{i-1}^{c2} \\ \overline{I}_{i-1}^{c3} \\ \overline{I}_{i-1}^{C} \end{bmatrix} = \left[X_i\right]\cdot \begin{bmatrix} \overline{U}_{i}^{c1} \\ \overline{U}_{i}^{c2} \\ \overline{U}_{i}^{c3} \\ \overline{U}_{i}^{C} \\ \overline{I}_{i}^{c2} \\ \overline{I}_{i}^{c3} \\ \overline{I}_{i}^{C} \end{bmatrix} + \left[Y_i\right]\cdot \overline{I}^F + \left[W_i\right]\cdot \overline{\Psi}_{C1,i-1} + \left[Z_i\right]\cdot \overline{\Psi}_{C2,i} \qquad (10)$$

where $[X_i]$, $[Y_i]$, $[W_i]$ and $[Z_i]$ are characteristics matrices of the considered part of the network.

# 4 Solution of the equations

Combining the input/output relations of every part of the system like illustrated in [5], the matrix equation of the whole MV network, included the interconnected earthing system, is found:

$$\begin{bmatrix} \overline{E}_{c2}-\overline{E}_{c1} \\ \overline{E}_{c3}-\overline{E}_{c2} \\ 0 \\ 0 \end{bmatrix} = [S]\cdot\prod_{i=1}^{h}\left[A_i\right]\cdot\prod_{i=h+1}^{n}\left[C_i\right]\cdot\left[D_n\right]\cdot\begin{bmatrix} \overline{U}_n^{c2} \\ \overline{U}_n^{c3} \\ \overline{I}_n^{C} \end{bmatrix} +$$

$$+[S]\cdot\prod_{i=1}^{h-1}\left[A_i\right]\cdot\left[B_h\right]\cdot\overline{I}_F + \qquad (11)$$

$$+[S]\cdot\left[\Phi_{C1}\right]\cdot\begin{bmatrix} \overline{\Psi}_{C1,0} \\ \overline{\Psi}_{C1,1} \\ \ldots \\ \overline{\Psi}_{C1,n-1} \end{bmatrix} + [S]\cdot\left[\Phi_{C2}\right]\cdot\begin{bmatrix} \overline{\Psi}_{C2,1} \\ \overline{\Psi}_{C2,2} \\ \ldots \\ \overline{\Psi}_{C2,n} \end{bmatrix}$$

where [S] is the characteristic matrix of the HV/MV station, $[A_i]$ e $[B_i]$ are the ones related to the generic $i^{th}$ section of MV line above the fault location, $[C_i]$ is the one related to the generic section below the fault location, $[D_n]$ is a matrix that has been introduced to include in the model the boundary condition at the end of the last section of the MV line, and $[\Phi_{C1}]$ and $[\Phi_{C2}]$ are two matrices that introduce in (11) the proximity effect. A simple way to calculate the various matrices in (11) is described in [5].

Eqn. (11) represents an undercostrained system of 4 equations with 4+n unknowns. A way to solve it is the following:

STEP 1: ignore the proximity effect so as to obtain a solvable system of 4 equations with 4 unknowns;

STEP 2: solve the system and find the currents flowing through the earth electrodes of the substations;

STEP 3: calculate the terms $\overline{\Psi}_{C1,i}$ and $\overline{\Psi}_{C2,i}$ using equation (3);

STEP 4: evaluate the error

$$e\% = \frac{\max\left\{\overline{\Psi}_{C1,i}, \overline{\Psi}_{C2,i}\right\}_k - \max\left\{\overline{\Psi}_{C1,i}, \overline{\Psi}_{C2,i}\right\}_{k-1}}{\max\left\{\overline{\Psi}_{C1,i}, \overline{\Psi}_{C2,i}\right\}_k}.100$$

where k and k-1 indicate, respectively, the values just calculated and the value related to the previous calculation;

STEP 5: if e% is less than an acceptable value, the system is solved, otherwise insert the values just calculated of $\overline{\Psi}_{C1,i}$ and $\overline{\Psi}_{C2,i}$ in (11) and repeat the procedure from STEP 2 until e% is acceptable.

The iterative procedure, generally, converge after less than 10 iterations.

# 5 Application example

Using a software carried out by the Authors, the proposed methodology has been applied for studying the network whose characteristics are reported in Table 1.

Table 1 – Characteristics of the network.

| | |
|---|---|
| Nominal voltage of the network [kV] | 20 |
| Distance between the substations [m] | 300 |
| Earth resistance of the substations [Ω] | 5-20 |
| Number of substations | 20 |
| Earth bulk resistivity [Ω·m] | 100-1000 |
| Earth resistance of the HV/MV station [Ω] | 0.1 |
| Resistance per unit length of the phase conductor [Ω/km] | 0.387 |
| Phase conductor diameter [mm] | 8.1 |
| Mean distance between the phase conductors [mm] | 8.3 |
| Mean distance between the phase conductor and the bare buried consuctor [mm] | 100 |
| Capacitance per unit length between the phase conductor and the bare buried conductor [μF/km] | 0.124 |
| Cross section of the bare buried conductor [mm$^2$] | 35 |
| Resistance per unit length of the bare buried conductor [Ω/km] | 0.52 |
| Bare buried conductor diameter [mm] | 7.55 |

Fig. 7-10 show, respectively, the rate $I_E/I_F$% between the current flowing through each earth electrode and the fault current, for a single-line-to-earth fault at the 10$^{th}$ substation, obtained considering (PE) and ignoring (No PE) the proximity effect.

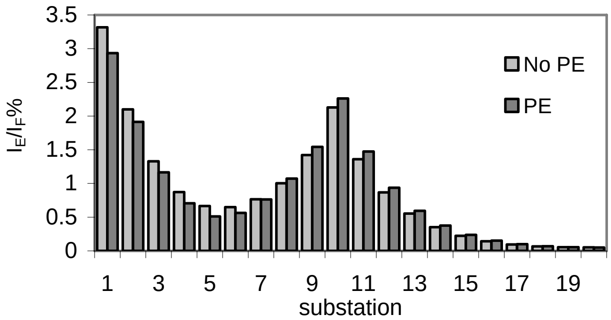


Fig 7. Rate $I_E/I_F$% for ρ=100Ωm, $R_E$=5Ω.

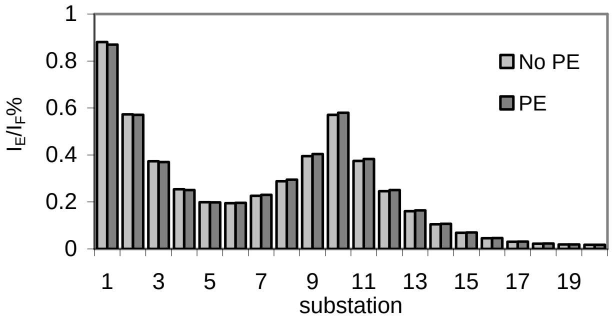


Fig 8. Rate $I_E/I_F$% for ρ=100Ωm, $R_E$=20Ω.

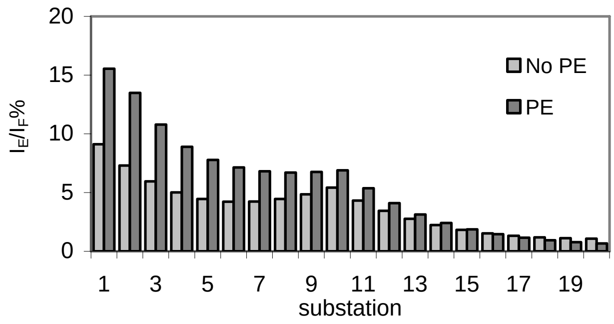


Fig 9. Rate $I_E/I_F$% for ρ=1000Ωm, $R_E$=5Ω.

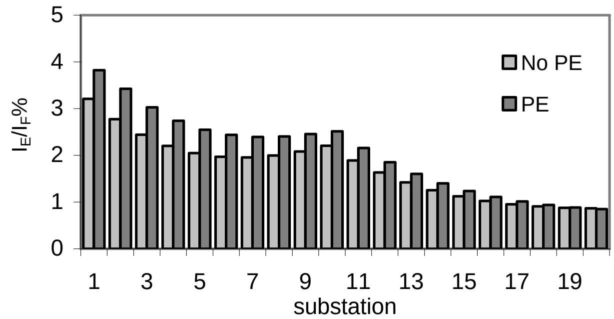


Fig 10. Rate $I_E/I_F$% for ρ=1000Ωm, $R_E$=20Ω.

The diagrams show that using buried conductor the current flowing through the earthing systems of the substations is reduced to few percents of the total fault current (15% in the worst case in Fig. 9). Consequently, the benefits obtainable in terms of reduction of dangerous touch and step voltages within substations' areas are enormous.

In Fig. 11 is shown the rate $I_{EC}/I_F$% between the current flowing through the bare buried conductor and the fault current. The case represented in Fig.11 illustrates that the parts of the bare buried conductors disperse in the soil percentages of the fault current less different.

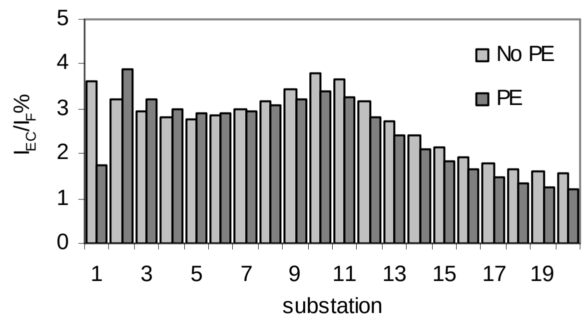


Fig 11. Rate $I_{EC}/I_F$% for ρ=1000Ωm, $R_E$=5Ω.

Moreover, the results show that in presence of good soil resistivity (100Ω·m) the proximity effect can be neglected with any significant error in the evaluation of the current flowing through the earth electrodes. On the contrary for soil with high resistivity, neglecting the proximity effect, can lead to errors that can be very high (41% at the 1st substation and 21% at the faulted one in Fig.9). Errors are as smaller as higher is the earth resistance of the earth electrodes of the substations.

## 6 Conclusion

The results of the study show the important consequences of the interconnection of earthing systems within MV networks. The use of bare buried conductor as interconnection elements considerably reduces the earth current at every substation, despite the proximity effect. This reduction is due to two factors:

1. bare buried conductors divide the fault current within all the interconnected earth electrodes;
2. bare buried conductors act as auxiliary earth electrodes injecting in the soil a great part of the fault current.

This strong reduction of the currents flowing through the earth electrodes of the substations, and the subsequent reduction of the earth potential rise, suggest the possibility of connecting the neutral point of the LV system supplied by each substation to the same earthing system of the substation without consequence for the insulation of the LV devices.

Carrying out this connection, a further reduction of the earth resistances of the substations is obtained and is promoted the formation of a GES. Indeed, the neutral conductor of the LV network is thickly connected to earth directly and through the pipelines of water and gas distribution networks.

Using the model presented in the paper and by the means of suitable software it's possible to analyze the behavior of an interconnected earthing system inside an urban area and to provide useful information about the presence of a GES.

If in any point of the MV network touch and step voltages don't exceed the limits imposed by [1] for any possible fault condition, the interconnected earthing system is a GES.

An analysis carried out using a simple PC is of course much more economical than doing a series of measurements of earth impedances or touch and step voltages.

However, such an analysis must be supported by a great precision in the collection of all the data, such as distances between the substations, earth resistivity, characteristics of the cables and of the buried conductors, geometrical and electrical characteristics of the earth electrodes.

Another aspect that must be considered is the presence of connections between earth electrodes and pipelines or other metallic elements not belonging to the electrical system. This aspect is always of difficult evaluation and the problem is often solved by using approximate expressions or by neglecting the presence of these elements on the side of safety.

Anyway the model proposed in this paper wants to give its contribution to increase the precision of the analysis. In particular the introduction of a model to consider the proximity effect can be very useful for all the cases in which the interconnection between the earth electrodes is carried out by bare buried conductors but also by the metal sheathes of uncoated cables.

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