POLITECNICO DI TORINO
Repository ISTITUZIONALE

Global Earthing Systems: Characterization of Buried Metallic Parts

Original
Global Earthing Systems: Characterization of Buried Metallic Parts / Cafaro, Giuseppe; Montegiglio, Pasquale; Torelli, Francesco; Colella, Pietro; Pons, Enrico; Tommasini, Riccardo; Valtorta, Giovanni. - ELETTRONICO. - (2016), pp. 1-6. (Intervento presentato al convegno 16th International Conference on Environment and Electrical Engineering (EEEIC) tenutosi a Florence (Italy) nel 7-10 June 2016) [10.1109/EEEIC.2016.7555723].

Availability:
This version is available at: 11583/2659080 since: 2020-01-28T17:34:08Z

Publisher:
IEEE

Published
DOI:10.1109/EEEIC.2016.7555723

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)

23 September 2024

Global Earthing Systems: Characterization of Buried Metallic Parts

Giuseppe Cafaro, Pasquale Montegiglio, and Francesco Torelli
DEI
Politecnico di Bari
Bari, 70126, Italy
Email: pasquale.montegiglio@poliba.it

Pietro Colella, *Member, IEEE*, Enrico Pons, *Member, IEEE*, and Riccardo Tommasini, *Member, IEEE*
DENERG
Politecnico di Torino
Torino, 10129, Italy
Email: pietro.colella@polito.it

Giovanni Valtorta
Enel Distribuzione SpA
Roma, 00198, Italy
Email: giovanni.valtorta@enel.com

***Abstract*—International Standards IEC 61936-1 and EN 50522 define a Global Earthing System (GES) as the earthing network, created by the interconnection of local earthing systems, that should guarantee the absence of dangerous touch voltages. This is achieved through two effects: the division of the earth fault current between many earthing systems and the creation of a quasi equipotential surface. The second effect can be enhanced by the presence of buried metallic parts, such as light poles and water/gas pipelines, that can modify the earth surface potential profile. In order to characterize these buried conductors, an extensive measurement campaign was organized; in order to determine the resistance to earth of these buried conductors a simplified measurement protocol has been applied to more than 800 metallic objects. In this paper, the measurement set-up, the results and their analysis are reported.**

***Index Terms*—Electrical safety; earth electrode; earthing system; extraneous-conductive-part; global earthing system; grounding; MV distribution faults; power distribution faults; indirect contacts; resistance to earth.**

I. INTRODUCTION

MV distribution systems in densely populated areas, such as residential and industrial zones, normally consist of a large number of MV/LV substations which are close to each other and interconnected (at least) through MV cables sheaths [1].

This tight interconnection of earthing systems (ESs) makes for an overall grounding network, which may cover large areas. In case of a single line to ground fault (SLGF), this provides two main effects:

- a distribution of the fault current between the grounding electrode of the faulty substation and the interconnected installations (neighbouring MV/LV substations, water/gas pipeline, etc.) [1], [2], [3];
- a smoothing of the Earth Potential Profile (EPR), reducing the hazardous voltage gradients [4], [5].

What previously mentioned is the basis for the Global Earthing System (GES) definition provided by the International Standards IEC EN 61936-1 and EN 50522: *"equivalent earthing system created by the interconnection of local earthing systems that ensures, by the proximity of the earthing systems, that there are no dangerous touch voltages"* [6] [7].

However, even if the physical phenomena related to the GES definition are now almost clear, no official practical guidelines are given in any standard yet. The main problem is that it is quite simple to evaluate the behavior of a specific system, while it is difficult to produce general guidelines, valid in all the possible different situations, based on simple rules easy to verify [8], [9], [10].

The GES effects can be enhanced by other several metallic parts, such as LV ESs, water/gas pipelines, railway and tramway tracks. In fact, these elements are commonly widespread in city centers, urban or industrial areas, that is, where GESs can normally be found [7], [11].

Unfortunately, the geometrical and electrical properties of these elements are not available and, therefore, quantifying their contribution is quite difficult.

In order to characterize these elements, the main parameter of interest is their resistance to earth. For this purpose a simplified measurement protocol has been applied to more than 800 metallic objects by Enel Distribuzione, the main Italian Distribution System Operator (DSO). In this paper, the adopted experimental setup and the measurement results are shown. Furthermore, a statistical analysis is presented, considering the influence of the soil resistivity and the types of neighborhood (old town city center, recently built neighborhood and suburbs).

II. MEASUREMENT CAMPAIGN

In this section, the measuring circuit and the criteria adopted for the selection of the measurement sites are described,

A. Measurement setup

The main goal of this paper is the characterization of metallic parts buried in urban areas where a GES may exist. For this purpose, the resistance to earth of light poles, gas and water pipes, fire hydrants, fences and similar elements has been measured during the campaign. Due to the large number of tests conducted (more than 800) a simplified methodology

This paper was developed as part of the research "METERGLOB" co-funded by the CCSE (today CSEA, Cassa per i Servizi Energetici e Ambientali) with the participation of six partners: Enel Distribuzione, Istituto Italiano del Marchio di Qualitá IMQ, Politecnico di Bari, Politecnico di Torino, Universitá di Palermo and Sapienza Universitá di Roma.

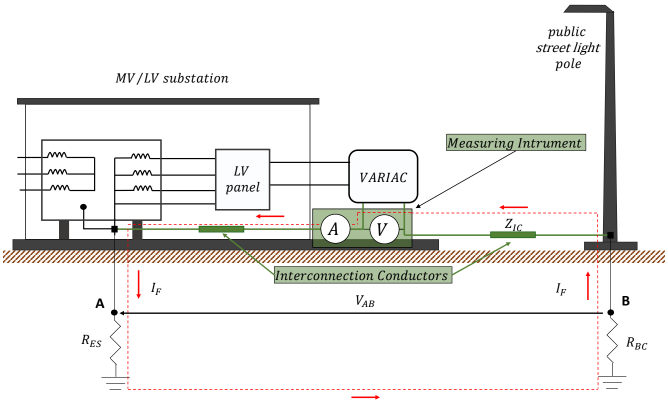

Figure 1. Measuring setup.

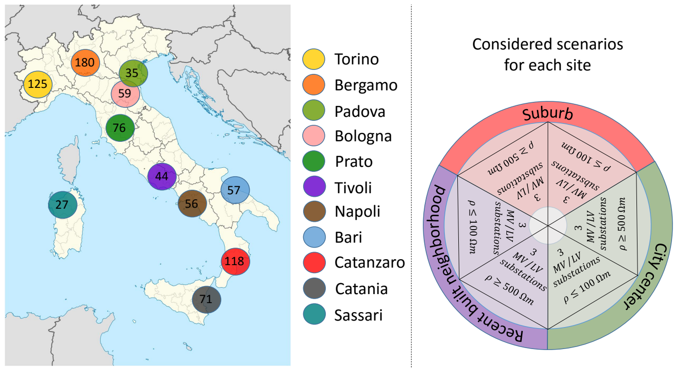

Figure 2. On the left, measurement sites: values represent the number of tests carried out in the relative location; on the right, the characteristics of the 18 MV/LV substations considered for each site.

was adopted, which required the subsequent calculation of the quantity of interest. The measuring setup is depicted in Fig. 1. Briefly, the earthing system of the MV/LV substation and the buried conductor under test was connected to a variable auto-transformer (VARIAC), which controlled the circulating current. The impedance Z_S of the loop created by the resistance to earth of the MV/LV substation earthing system R_{ES} and the resistance to earth of the generic buried conductor under test R_{BC} was then measured. For safety reasons the flowing current I_F was kept below 5 A. The two-wires impedance measurement procedure was adopted, adequately taking into consideration the interconnection conductor impedance Z_{IC}.

Since the imaginary part of Z_S is significantly lower than the real one, in this paper only $R_S = Re\{Z_S\}$ is taken into account.

The resistance to earth R_{ES} is a known value, periodically measured by the DSO. By subtracting it from R_S, an assessment of the resistance to earth of the buried conductor R_{BC} can be obtained with an approximation that depends on the R_{ES} uncertainty and on the interference level between the two electrodes. The problem of the interference will be addressed and discussed in Section III.

B. Sample selection

For the execution of the tests reported in this paper, measurement sites were selected in several Italian municipalities. Fig. 2 shows the involved areas and the number of tests carried out in each location. As typical cases of GES are in city centers, urban or industrial areas [7], municipalities characterized by having, at least, a population density of 500 inhabitants per square kilometer were selected. Where possible, in order to cover each typical urban scenario, the choice of the MV/LV substations was oriented on sites located within:

1) city centers;
2) suburbs;
3) recently built neighborhood (built up in the last 5 years).

Sites characterized by different soil resistivity were chosen, in order to get a sample as varied as possible.

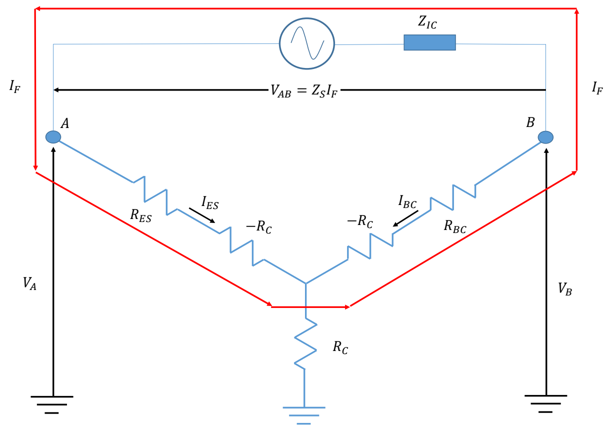

Figure 3. Interference phenomenon equivalent circuit.

Fig. 2 summarizes, for each measurement site, the properties of the considered urban contexts where MV/LV substations are located.

The absence of significant electromagnetic disturbance sources (e.g. antennas, close overhead lines, etc.) was also preliminary verified.

III. Interference Phenomenon: A Theoretical Point of View

The adopted simplified measurement methodology allows the assessment of the R_{BC} value with a certain approximation. Not considering the uncertainty on R_{ES}, the measured value reflects the true earth resistance of the buried conductor only if the interference phenomenon with the ES of the MV/LV substation can be neglected. In this section, a short summary of this interference phenomenon is presented.

As known in literature [5], [12], [13], the interference phenomenon between two electrodes buried in the soil can be represented, in *quasi-static* condition ($50Hz$), by pure resistive parameters. The star of connected resistors reported in Fig. 3 (solid blue line), arises, after simple mathematical manipulations, from the following linear system:

$$\begin{cases} V_A = R_{ES}I_{ES} + R_C I_{BC} \\ V_B = R_C I_{ES} + R_{BC}I_{BC} \end{cases} \quad (1)$$

With reference to the typical test case considered for this work:

- R_{ES} is the equivalent resistance of the entire grounding network made up by the interconnected ESs of the MV/LV substations. It may also include the LV neutral *reinforcement groundings* [11];
- R_{BC} is the earth resistance of the metallic part under test. Depending on the effectiveness of its contact with the ground, its extension and electrical continuity, R_{BC} may assume low values (≤ 1 Ω);
- I_{ES} and I_{BC} are the currents flowing through R_{ES} and R_{BC} respectively;
- R_C is the *mutual transfer resistance*. It can be considered as the transferred voltage on the "passive" grounding electrode when the "active" one is leaking a unitary current [12] and it is defined as follows:

$$R_C = \alpha R_{ES} = \beta R_{BC} \quad (2)$$

where

$$\alpha = \left.\frac{V_B}{V_A}\right|_{I_{BC}=0} < 1; \quad \beta = \left.\frac{V_A}{V_B}\right|_{I_{ES}=0} < 1 \quad (3)$$

The stronger is the interference phenomenon, the higher are coefficients α and β.

According to eq. (2), R_C is always lower than the smallest between R_{ES} and R_{BC}:

$$R_C < \min\{R_{ES}, R_{BC}\} \quad (4)$$

The series resistance R_S, measured in the test, can be analytically expressed as follows:

$$R_S = R_{ES} + R_{BC} - 2R_C \quad (5)$$

Subtracting R_{ES} from R_S, the resistance to earth of the buried conductor R_{BC} can be computed, save for $2R_C$.

The lower is the interference phenomenon, the lower is the resistance R_C.

IV. Measurement results

The total number of measurements is reported in Table I. In the second column, their distribution with reference to the metal object type is also shown. The third column reports the number of cases where it was not possible to inject a current greater than 1 A without increasing the voltage level over the safety limit (50 V). For the particular case of light poles, this can be due to the fact that, in the installation phase, concrete is usually poured with a plastic pipe to preserve the hole for the pole installation. If the plastic pipe used as a mould is not removed, the result is that the pole will be isolated from ground. In the case of pipelines, instead, this is probably due to the increasing adoption of non metallic pipes in the water (and gas) distribution networks. From the forth column it can be noticed that a number of 44 abnormal data (unstable output of the instrument) was discarded.

The measured values of R_S are shown in Fig. 4 - Fig. 7. The majority of them is lower than 20 Ω.

In Fig. 8, the resistance to earth of the MV/LV substations, R_{ES}, measured by the DSO, is reported. With few exception, the measured values are extremely low: the mean value is lower than 1Ω, which is typical of the overall distribution grounding network equivalent resistance.

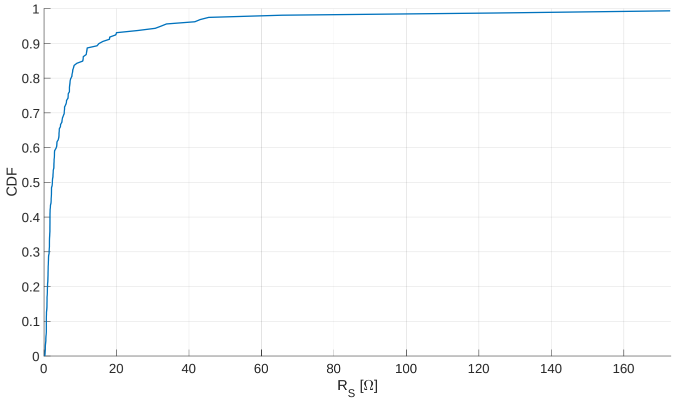

Figure 4. Cumulative distribution function (CDF) of R_S for light poles.

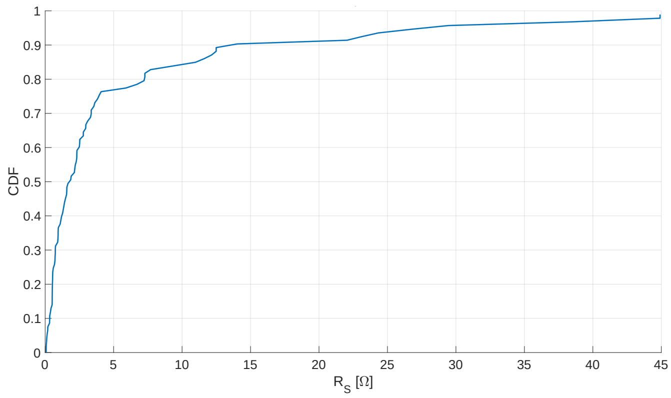

Figure 5. Cumulative distribution function (CDF) of R_S for gas pipelines.

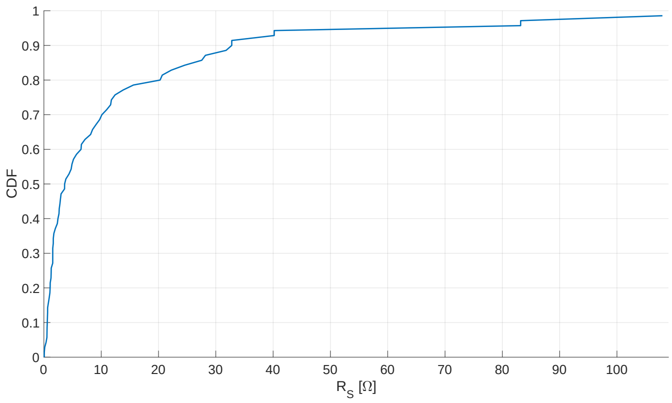

Figure 6. Cumulative distribution function (CDF) of R_S for water pipelines.

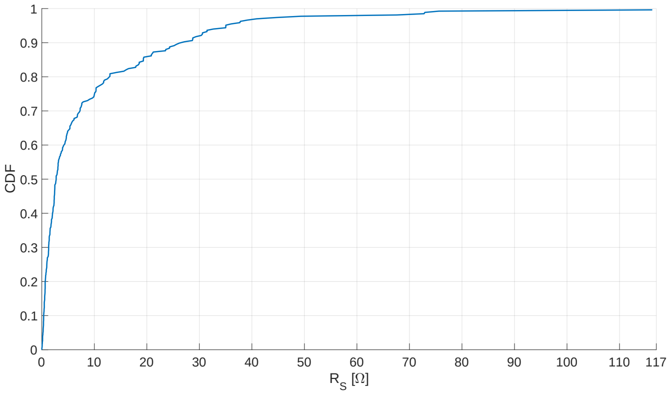

Figure 7. Cumulative distribution function (CDF) of R_S for other buried conductors.

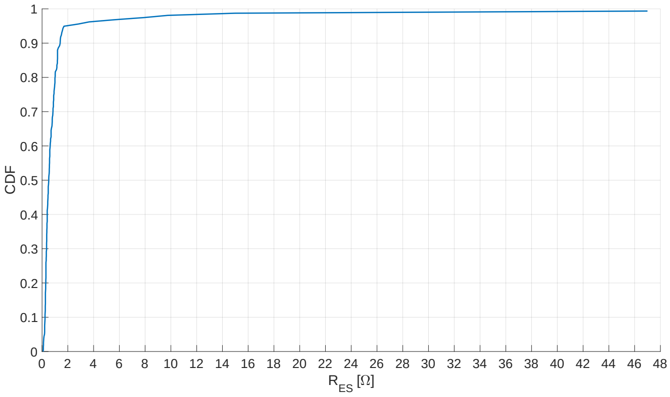

Figure 8. Cumulative distribution function (CDF) of the earth resistance R_{ES} of the MV/LV substations involved in the measuring campaign.

As shown in the previous section, subtracting from R_S the resistance to earth of the MV/LV substation earthing system, the following quantity can be evaluated:

$$R^*_{BC} = R_{BC} - 2R_C \tag{6}$$

For each urban scenario, the minimum and the maximum of R^*_{BC} are shown in Fig. 9. The lines between vertical bars intercept the relative mean values. Below each scenario, the number of measurements is also reported.

The analysis of Fig. 9 shows negative R^*_{BC} for same cases. According to eq. (6), this occurs when $2R_C > R_{BC}$, that is when there is a strong interference phenomenon and the values R_{ES} and R_{BC} are comparable. Moreover, it can be observed

Table I
NUMBER OF MEASUREMENTS

Buried conductor type	Total	High earth resistance	Discarded
Light Poles	204	36	9
Gas Pipelines	107	11	3
H_2O Pipelines	112	32	10
Other	415	126	22
TOTAL	**838**	**205**	**44**

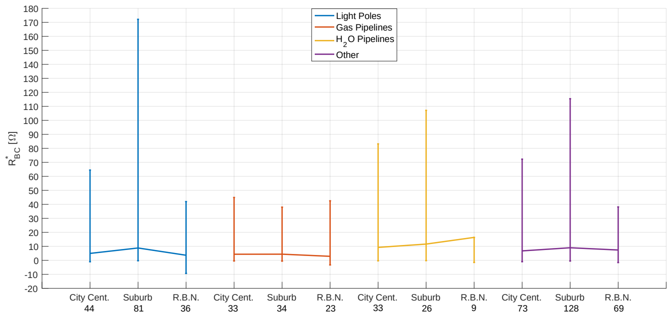

Figure 9. R^*_{BC} measurements (minimum, mean and maximum value) for each urban scenario (City Centers, Suburbs, Recently Built Neighborhoods).

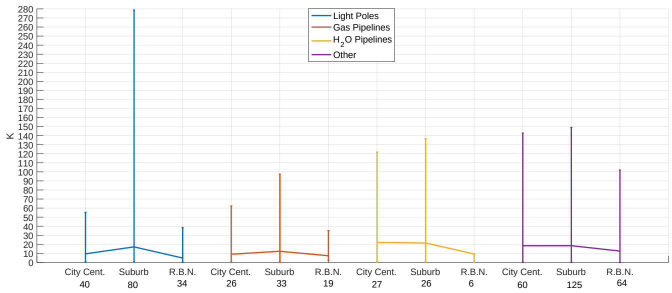

Figure 10. K values (minimum, mean and maximum) for each urban scenario (City Centers, Suburbs, Recently Built Neighborhoods).

that the R^*_{BC} mean values are similar, independently of both the buried conductor type and the urban scenarios.

For all the cases, the minimum and mean values of R^*_{BC} are close each other. This means that the highest values refer to a very limited set of samples.

The resistance to earth of an electrode depends on its geometry and on the soil resistivity. Since the measurements were all carried out in a 100 m radius area around the considered substation, in first approximation it is reasonable to consider both the electrodes buried in a soil with the same properties. So, to decouple measurements from the resistivity parameter, the coefficient K was defined as:

$$K = \frac{R_S}{R_{ES}} \tag{7}$$

Fig. 10 shows K values, grouped with reference to scenarios. It was not possible to evaluate K for all the cases since, for a small number of MV/LV substations, R_{ES} was not available. As the R_{ES} values are comparable for the most considered substations (with reference to Fig. 8), Fig. 10 is representative of the R^*_{BC}.

The same conclusions given for Fig. 9 are generally valid for K minimum, mean and maximum values. This suggests that the large extension of metallic objects plays a predominant role against the soil resistivity.

Moreover, as shown in appendix VI-B, by the knowledge of K and R_{ES}, it is possible to evaluate the maximum and minimum values of R_{BC}.

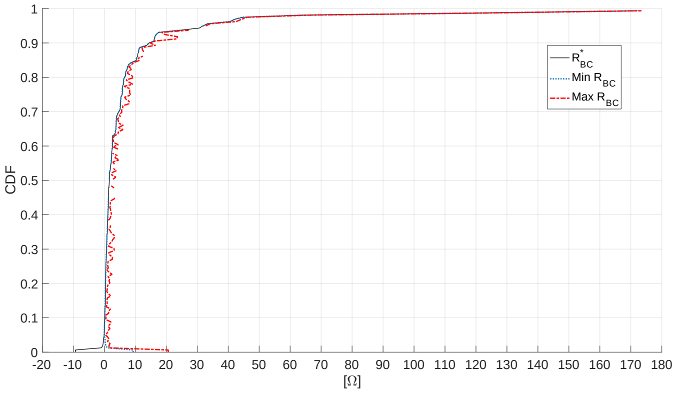

Figure 11. Light poles: cumulative distribution function (CDF) of R^*_{BC}. For each point, the theoretical minimum and maximum values of R_{BC} are shown.

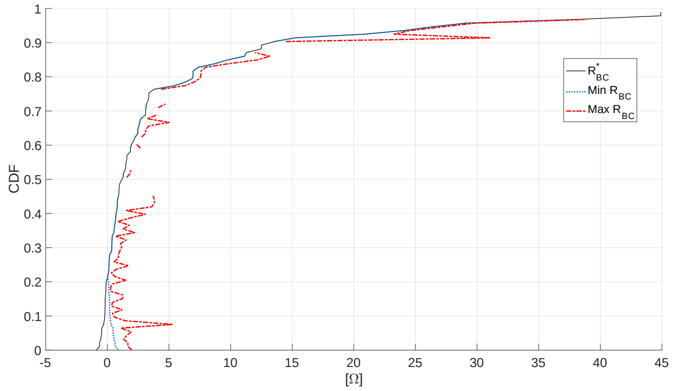

Figure 12. Gas pipeline: cumulative distribution function (CDF) of R^*_{BC}. For each point, the theoretical minimum and maximum values of R_{BC} are shown.

In Fig. 11 - 13, the R^*_{BC} and the maximum and minimum values of R_{BC} (evaluated according to eq. (11)) are reported for each kind of metallic object involved in the measurement campaign.

Maximum and minimum R_{BC} missing values in Fig. 11 - 13 are due to the lack of knowledge of the relative substation R_{ES}. As previously highlighted, for these cases, the evaluation of K coefficient cannot be carried out.

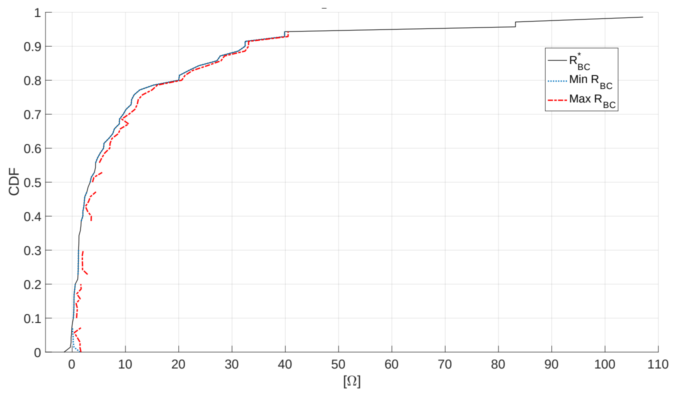

Figure 13. Water pipeline: cumulative distribution function (CDF) of R^*_{BC}. For each point, the theoretical minimum and maximum values of R_{BC} are shown.

As expected, the distance among the three curves is quite short for all the considered buried conductors. This means that the measurement procedure presented in this work allows a good evaluation of the resistance to earth of a buried conductor.

Moreover, as shown in Fig. 11 - Fig. 13, the minimum R_{BC} and the measured R^*_{BC} often present similar values. In accordance to (6), this means that R_C must be small with reference to R_{BC} for the most considered buried metallic conductors. In these cases the interference phenomenon has not a significant role in the evaluation of R_{BC}.

V. Conclusion

The total number of data collected by the measurements campaign is 838. Not considering the discarded 44 abnormal values (unstable output of the instrument), about 25% of the buried conductors present a very high value of resistance to earth.

For the 587 remaining buried conductors (about 70% of the total number of collected data), independently of the type and of the urban scenarios, an average earth resistance value of 10Ω can be considered.

In order to decouple measurements from the resistivity parameter, the ratio K between the measured resistance R_S and the resistance to earth of the MV/LV substation ES was computed. Also in this case, no significant differences can be noticed with reference to both the type of buried conductors and the urban scenario.

VI. Appendix

A. *K Analitical Expression*

Dividing both sides of (5) by R_{ES} and considering that $R_C = \beta R_{BC}$, it is possible to write the K coefficient expression as a function of β and the ratio R_{BC} / R_{ES}:

$$K = \frac{R_S}{R_{ES}} = 1 + (1 - 2\beta)\,\frac{R_{BC}}{R_{ES}} \qquad (8)$$

B. *Maximum and minimum values of R_{BC}*

From the equation (8) it is possible to write β coefficient as a function of K:

$$\beta = \frac{1}{2}\left(1 - \frac{(K-1)\,R_{ES}}{R_{BC}}\right) \qquad (9)$$

With reference to (3), it is here recalled that coefficient β represents the portion of EPR assumed by the metallic part under test (which is supposed leaking a unitary current) that is transferred on the ground electrode of the considered substation. So it can be deduced that $0 \leq \beta < 1$. Moreover, with reference to eq. (2), it must be $\beta R_{BC} < 1 \cdot R_{ES}$. Taking into account that R_{BC} resistance must be positive, it is possible to write the following equation set:

$$\begin{cases} 0 \leq \beta < 1 \\ \beta R_{BC} < 1 \cdot R_{ES} \\ R_{BC} > 0 \end{cases} \qquad (10)$$

The solution of eq. set (10) identifies two different ranges of R_{BC} values as a function of K.

$$R_{BC} \in \begin{cases} \left[(K-1)\, R_{ES}, (K+1)\, R_{ES} \right], & K \geq 1 \\ \left[(1-K)\, R_{ES}, (K+1)\, R_{ES} \right], & K < 1 \end{cases} \qquad (11)$$

So, for each measured value of K, it is possible to evaluate the minimum and maximum value of R_{BC}. The more the inequalities (12) are true, the smaller is the R_{BC} range in (11).

$$K << 1 \quad or \quad K >> 1 \qquad (12)$$

An application example of the method to compute the minimum and the maximum values of R_{BC} is now provided. The considered scenario is reported in Fig. 14: a square electrode (ES) and an earthing rod (BC) are buried at 0.5 m under the soil surface. Geometrical details are reported in Table II. The scenario was modeled through the Maxwell's Subareas Method (MaSM) [5]. The resistances R_{ES} and R_S were computed and reported in Table III. The K ratio, evaluated according to eq. (7), is equal to 13.7.

From the set of equations (11), the minimum and maximum values of R_{BC} were calculated. Their values are respectively 66.2 Ω and 76.6 Ω.

In order to verify the range, the "true" value of R_{BC} was then computed. It is equal to 72.1 Ω. As expected, it is in the forecasted range.

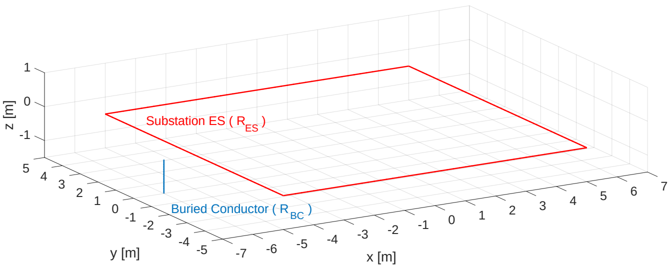

Figure 14. Example of application: considered layout..

Table II
EXAMPLE OF APPLICATION: GEOMETRICAL DETAILS

Quantity	Values
Length of square ES	10 m
Length of the earthing rod BC	1 m
Distance between ES and R_{BC}	1 m
Cross section of ES and BC electrodes	9 mm
Soil resistivity	100 Ωm

Table III
EXAMPLE OF APPLICATION: RESULTS

Quantity	Values
R_{ES}	5.2Ω
R_S	71.4Ω
K	13.7
Min R_{BC}	66.2Ω
Max R_{BC}	76.6Ω

REFERENCES

[1] E. Pons, P. Colella, R. Napoli, and R. Tommasini, "Impact of MV ground fault current distribution on global earthing systems," *Industry Applications, IEEE Transactions on*, vol. 51, no. 6, pp. 4961–4968, 2015.

[2] A. Campoccia, E. R. Sanseverino, and G. Zizzo, "Analysis of interconnected earthing systems of MV/LV substations in urban areas," in *Universities Power Engineering Conference, 2008. UPEC 2008. 43rd International*. IEEE, 2008, pp. 1–5.

[3] P. Colella, R. Napoli, E. Pons, R. Tommasini, A. Barresi, G. Cafaro, A. De Simone, M. Di Silvestre, L. Martirano, P. Montegiglio *et al.*, "Current and voltage behaviour during a fault in a HV/MV system: Methods and measurements," in *Environment and Electrical Engineering (EEEIC), 2015 IEEE 15th International Conference on*. IEEE, 2015, pp. 404–409.

[4] G. Parise, L. Parise, and L. Martirano, "Identification of global grounding systems: the global zone of influence," *Industry Applications, IEEE Transactions on*, vol. 51, no. 6, pp. 5044–5049, 2015.

[5] E. Pons, P. Colella, R. Tommasini, R. Napoli, P. Montegiglio, G. Cafaro, and F. Torelli, "Global earthing system: can buried metallic structures significantly modify the ground potential profile?" *Industry Applications, IEEE Transactions on*, vol. 51, no. 6, pp. 5237–5246, 2015.

[6] *Power installations exceeding 1 kV a.c., Part 1: Common rules*. IEC EN 61936-1, 07 2011.

[7] *Earthing of power installations exceeding 1 kV a.c.* CEI EN 50522, 07 2011.

[8] P. Colella, E. Pons, and R. Tommasini, "The identification of global earthing systems: a review and comparison of methodologies," 2016, Environment and Electrical Engineering (EEEIC), 2016 IEEE 16th International Conference on.

[9] G. Parise, L. Parise, and L. Martirano, "Single grounding system intrinsically safe and global grounding system safe as set," Environment and Electrical Engineering (EEEIC), 2016 IEEE 16th International Conference on.

[10] M. L. Di Silvestre, L. Dusunchet, S. Mangione, and G. Zizzo, "On the effects of HV/MV stations on global grounding systems," 2016, Environment and Electrical Engineering (EEEIC), 2016 IEEE 16th International Conference on.

[11] G. Cafaro, P. Montegiglio, F. Torelli, A. Barresi, P. Colella, A. D. Simone, M. L. D. Silvestre, L. Martirano, E. Morozova, R. Napoli, G. Parise, L. Parise, E. Pons, E. R. Sanseverino, R. Tommasini, F. Tummolillo, G. Valtorta, and G. Zizzo, "Influence of LV neutral grounding on global earthing systems," in *Environment and Electrical Engineering (EEEIC), 2015 IEEE 15th International Conference on*, June 2015, pp. 389–394.

[12] V. Cataliotti and A. Campoccia, *Impianti di terra*. TNE, 2013.

[13] F. Freschi, M. Mitolo, and M. Tartaglia, "Interferences phenomena between separate grounding systems," *IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS*, vol. 50, no. 4, pp. 2853–2860, 2014.