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Earth Resistance Measurements in Urban Contexts: Problems and Possible Solutions

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***Abstract*—Both EN 50522 and IEEE Std. 81 propose the Fall of Potential Method (FPM) to carry out the measurement of the resistance to earth of an Earthing System (ES). However, in urban areas, the recommended distances between the ES and auxiliary electrodes are not easy to respect, due to the presence of buildings and tarmac. Moreover, unknown buried metallic parts, as well as the interconnection among the ESs made by the Distributor System Operator, could modify the earth potential profile of the area, affecting the measurement results. In this paper, the issues that could affect the measurement result if FPM is used in an urban context are presented. A parametric analysis, carried out with Comsol Multiphysics, quantifies the errors due to wrong positioning of the auxiliary electrodes with reference to the ES under test. In addition, a field measurement is described, emphasizing the main aspects that could compromise the results. Finally, practical suggestions to reduce errors are provided.**

I. Introduction

The international Standard EN 50522 prescribes that Earthing Systems (ESs) of MV/LV substations shall be dimensioned in order to avoid dangerous touch voltages [1].

According to EN 50522, the observance of permissible touch voltage is satisfied if one of the following conditions is verified:

1) the relevant installation becomes a part of a Global Earthing Systems (GES) [2]–[5];
2) the stipulation for the permissible touch voltage is proved, generally by measurements [6];
3) the earth potential rise (EPR) does not exceed specified safety thresholds, which are defined on the basis of the eventual adoption of recognized specified measures M, described in Annex E of EN 50522 [1]. As known, to evaluate the EPR, an estimation/measurement of the resistance to earth R_{ES} of the substation under test shall be carried out. One of the methods suggested by both EN 50522 and IEEE Std. 81 is the Fall of Potential Method (FPM) [1], [7].

In urban areas, FPM is not easy to be used, as several issues can affect the results. In particular, an underestimation of R_{ES} can be due to:

1) an erroneous positioning of auxiliary electrodes [8];
2) the interconnection of the ES under test with other ESs, through protective conductors (e.g. MV cable sheaths) [9];
3) the presence of unknown buried metallic parts, such as water pipes or bare buried earth conductors [10];
4) electromagnetic noises, created by electric systems located in the vicinity (e.g. urban light railways).

In this paper, the main aspects that should be considered using the FPM in an urban context are discussed. In particular, the problem of incorrect positioning of the auxiliary electrodes is analyzed through simulations in section III, while the problems of interconnections among ESs and presence of buried metallic parts are studied in sections II and IV.

To better explain the problems, theoretical explanations are supported by practical examples, acquired during field measurements.

II. Fall of potential method in urban contexts

The measuring setup of the FPM is depicted in Fig. 1 [11], [12]. As known, two auxiliary electrodes (C and P), lying on a straight line with the ES under test, are required. ES and auxiliary current electrode C are connected to a current generator, which injects the current I. The voltage V between ES and voltage probe P is measured. According to EN 50522 (Annex L), for an ES characterized by a maximum extension in measuring direction d, if the conditions reported in the set 1 are verified, R_{ES} can be computed by the ratio V/I [1].

$$\begin{cases} d_P \geq 2.5 \cdot d \\ d_P > 20m \\ d_C \geq 4 \cdot d \\ d_C > 40m \end{cases} \tag{1}$$

A helpful suggestion for the positioning of auxiliary electrodes can be found also in IEEE Std. 81 [7], [11], [13]. For small electrodes, if condition 2 is verified, R_{ES} can be computed without significant errors.

$$d_P = 62\% \cdot d_C \tag{2}$$

However, in an urban context, conditions (1) and (2) are not easy to meet since tarmac and buildings reduce the number of places where auxiliary electrodes can be positioned. For these reasons, the auxiliary current electrode and the voltage probe are often not optimally positioned, thus introducing an error in the earth resistance evaluation. The positioning problem

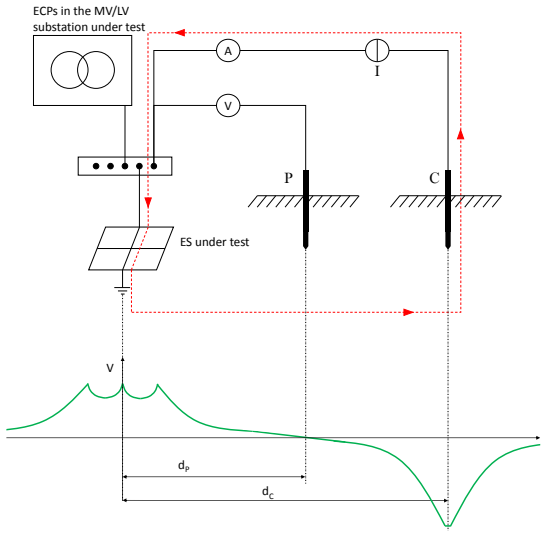

Figure 1. FPM measurement setup, current paths and earth potential profile.

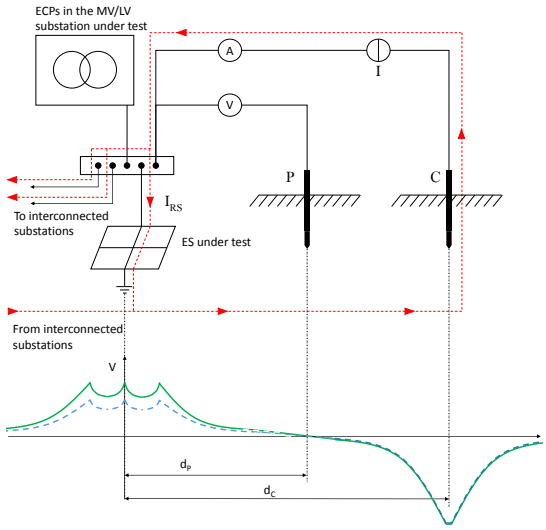

Figure 2. Error due to interconnection among ESs. The dashed blu line and the continuous green line represent the EPP for the scenario with and without interconnection, respectively.

will be addressed in section III; the other main aspects that should always be considered approaching earth measurement are instead discussed in the following paragraphs.

A. Interconnection among ESs

The interconnection among the ESs of the MV/LV substation through protective conductors, such as MV cable sheaths, should always be considered in earth measurement. In fact, as shown in Fig. 2, the current that flows through the ES under test can be just some percent of the total test current I [14], [15]. Consequently, EPR and R_{ES} can be underestimated.

If the MV/LV substation is under construction, a simple solution is the disconnection of the ES under test from other ESs. Vice-versa, if the MV/LV substation is already working, other strategies should be adopted. In fact, in order to carry out the measurement safely, before disconnecting the ES from the cable sheaths, the whole MV feeder shall be powered off, with a consequent service interruption that is generally considered unacceptable by Distribution System Operators (DSOs). An alternative solution is to use high frequency earth testers; the frequency shall be sufficiently high that the impedance of the interconnection conductors becomes relevant, representing a practically negligible shunt circuit to the earthing of the single ES.

B. Presence of buried metallic parts

Another point that should be considered in earth resistance measurements is the presence of buried metallic parts (BPs), which can belong to the earthing network (e.g. bare buried conductors) or not (e.g. water and gas pipes). These objects are commonly widespread in urban areas and usually have a large extension. Generally, no information about them is available during R_{ES} measurements. They can be interconnected to the ES or kept floating. According to their interconnection level and to their distance from the ES under test, they can modify the current field and the Earth Potential Profile (EPP) [10]. An

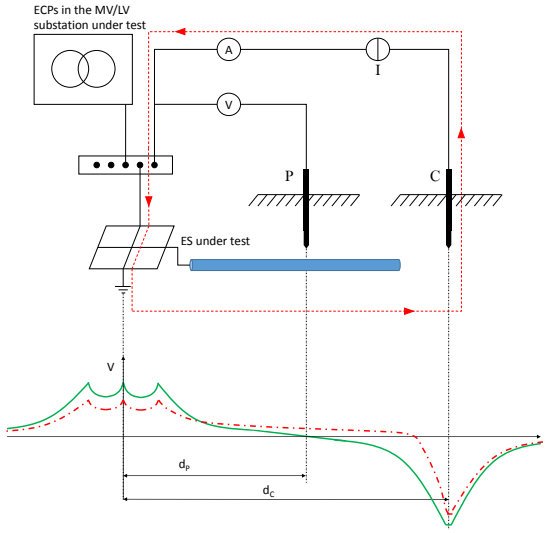

Figure 3. Error due to the presence of buried metallic parts, interconnected to the ES. The dot-dash red line and the continuous green line represent the EPP for the scenario with and without the buried metallic part, respectively.

unfavorable condition happens when the voltage probe P lies over a metallic object interconnected to the ES, as shown in Fig. 3. In this case, the reference potential given by P is far from zero and both EPR and R_{ES} are underestimated.

III. Positioning of Auxiliary Electrodes

As discussed in the previous section, standards EN 50522 and IEEE Std. 81 provide suggestions for the positioning of auxiliary electrodes (eq. (1) and eq. (2)) [1], [7]. However, the recommended distances are not easy to respect in urban contexts due to the presence of buildings and tarmac.

In order to quantify the error caused by an erroneous positioning of current electrode and voltage probe, a parametric analysis was carried out by Comsol Multyphisics, a

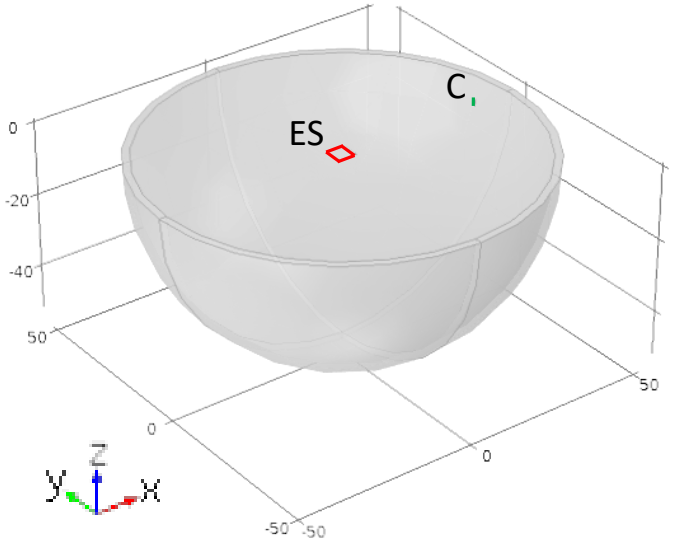

Figure 4. The implemented model. The ES and the auxiliary current electrode C are drawn in red and green lines, respectively.

commercial software based on Finite Element Method (FEM), already validated in previous papers [10], [16].

In particular, an ES of a MV/LV substation and an auxiliary current electrode are modeled in two scenarios, characterized by a different distance between their centers ($40\ m$ and $20\ m$ for scenario 1 and 2, respectively). Notice that, for the considered case, $40\ m$ is the acceptability threshold recommended by EN 50522 [1] for the distance d_C, as shown in eq. (1).

The objective is to quantify measurement errors due to the positioning of auxiliary electrodes. In this way, it will be possible to evaluate if the measurement can be considered reliable even if conditions (1) and (2) are not fully verified.

In paragraph III-A, details about the geometry and the materials adopted in the simulations are reported.

In paragraph III-B, the FEM settings are provided, with reference to the techniques chosen to model a theoretically infinite domain, such as the ground, and to the characteristics of the mesh. Furthermore, a control parameter adopted to evaluate the accuracy of the results is presented.

Finally, in paragraph III-C, the results of the parametric analysis are reported.

A. Geometry and Materials

The ES of the MV/LV substation was modeled as a square electrode, buried at $0.5\ m$ under the soil level, while the earth rod typically used as auxiliary current electrode is modeled as a cylinder. The soil was considered homogeneous, characterized by a resistivity of $100\ \Omega m$, while both the electrodes are made in copper. Other geometrical and electrical details are reported in Table I. The implemented model is depicted in Fig. 4, as well as the cartesian coordinate system: the ES and the auxiliary current electrode C are drawn in red and green lines, respectively.

Table I
GEOMETRICAL AND ELECTRICAL DETAILS

Symbol	Quantity	Values
L_{ES}	Square electrode length	$5\ m$
L_C	Auxiliary current electrode length	$1\ m$
$d_{C_{S1}}$	Distance between the centers of the electrodes for the Scenario 1	$40\ m$
$d_{C_{S2}}$	Distance between the centers of the electrodes for the Scenario 2	$20\ m$
t_{ES}	Square electrode conductor thickness	$5\ cm$
r_C	Auxiliary current electrode radius	$5\ cm$
rho_{cu}	Electrical resistivity of copper	$1.66 \cdot 10^{-8}\ \Omega m$
rho_{soil}	Electrical resistivity of the soil	$100\ \Omega m$

B. FEM settings

All the electric potentials relate to the reference earth, i.e. a part of the Earth whose electric potential is conventionally taken as zero, being outside the zone of influence of the earthing systems [1]. In order to model the unbounded domain correctly without increasing the size of the problem, the method based on spatial transformation was adopted [17]. This implementation maps the model coordinates from the local, finite-sized domain to a stretched domain. The inner boundary of this stretched domain coincides with the local domain, but at the exterior boundary the coordinates are scaled toward infinity [18]–[20]. In this way, it is possible to set the potential of the external boundary equal to $0\ V$.

The other boundary condition in the simulations concerns both the grounding electrodes. The square ES injects into the soil $1\ A$; the same current is "picked up" by the auxiliary current electrode.

In order to assess the accuracy of the simulation, current is used as control parameter: the currents flowing into the ground should be equal to the sum of currents flowing out of the boundary. Since the current injected by the square electrode is the same picked-up by the earth rod, the current flowing through the remaining not-isolated surface, i.e. the external ground boundaries, shall be equal to 0. The control parameter error (CPE) is evaluated by (3) and reported in Table II for each of the considered scenarios.

$$CPE = \iiint_S ||J_{out}(x,y,z)||\, dx\, dy\, dz \tag{3}$$

where: $||J_{out}(x,y,z)||$ is the normal current density (A/m^2) in the point with x,y,z coordinates ans S is the external ground surface, not considering the infinite element.

C. Results of the Parametric Analysis

The R_{ES} of the MV/LV substation earthing system under test, i.e. the square electrode, was computed by eq. (4):

$$R_{ES} = \frac{V}{I} = \frac{EPR_{ES} - V_P(x,y)}{I} \tag{4}$$

where:

- V is the voltage between the ES under test (square electrode) and the voltage probe P;

Table II
PARAMETRIC ANALYSIS RESULTS

Scenario #	CPE [V]	$(\mathbf{x},\mathbf{y})\|_{\mathbf{d_C}}$ [m]	$(\mathbf{x},\mathbf{y})\|_{\mathbf{d_P}}$ [m]	$\mathbf{R_{ES}}$ [Ω]	$\epsilon_\mathbf{r}$ [%]
1	0.000	$(40, 0)$	$(-20, 0)$	7.43	-11.19
1	0.000	$(40, 0)$	$(24.8, 0)$	8.37	0.07
2	0.000	$(20, 0)$	$(-10, 0)$	6.48	-22.60
2	0.000	$(20, 0)$	$(12.4, 0)$	8.37	0.04

- I is the test current, equals to 1 A in the simulations presented in this work;
- EPR_{ES} is the Earth Potential Rise of the ES;
- $V_P(x, y)$ is the potential of the voltage probe in the position identified by the coordinates x, y, considered equal to the potential of the soil surface in the same point.

The calculated values for R_{ES} are reported in Table II for the more relevant positions of the voltage probe, with reference to the suggestions of both EN 50522 and IEEE Std.81. The distance d_P requested by IEEE Std. 81 (eq. (2)) is 24.8 m and 12.4 m for scenario 1 and 2, respectively. To allow a comparison among the several configurations of auxiliary electrodes, a reference value R^*_{ES}, equals to 8.38 Ω, was computed with Comsol Multiphysics in a third simulation, where the only ES under test is present. In this way, the relative percentage error ϵ_r could be calculated.

According to the results reported in Table II, it can be observed that if eq. (2) is satisfied, it is possible to obtain extremely small percentage errors. However, if the voltage probe is not placed exactly in the required position, the errors quickly increase. This effect is the more evident, the nearest are the ES and the current electrode.

For new MV/LV substations, a good practice would be the fixed installation of the two auxiliary electrodes (C and P of Fig. 1) at a proper distance from the ES, so that the measurement of R_{ES} could be carried out in a simple and accurate way.

In Fig. 5 and 6, the isolines of the relative percentage error defined by the position of the voltage probe are reported.

According to these contour plots, it is evident that the errors rapidly decrease moving from the ES: for both the scenarios, when the voltage probe is placed at (-10, 0), an error of about -20% is obtained.

However, to get $\epsilon_e < 5\%$, a large distance between the ES and the voltage probe is required.

In addition, it can be noticed that the isolines are not symmetrical with reference to the ES. Dividing the ground in four areas (north ($y > 0$), south ($y < 0$), est ($x > 0$), west($x < 0$)), two asymmetries can be noticed. The first one between the west and east portions of ground with reference to the ES; the second one, between the north and west areas. Both are due to the presence of the auxiliary current electrode, which modifies the electric potential profile of the ground with reference to the case in which only ES is present. According to these results, contrary to what might be thought, it could be more convenient to place the voltage probe along the north or south directions, than on the west side. The common practice

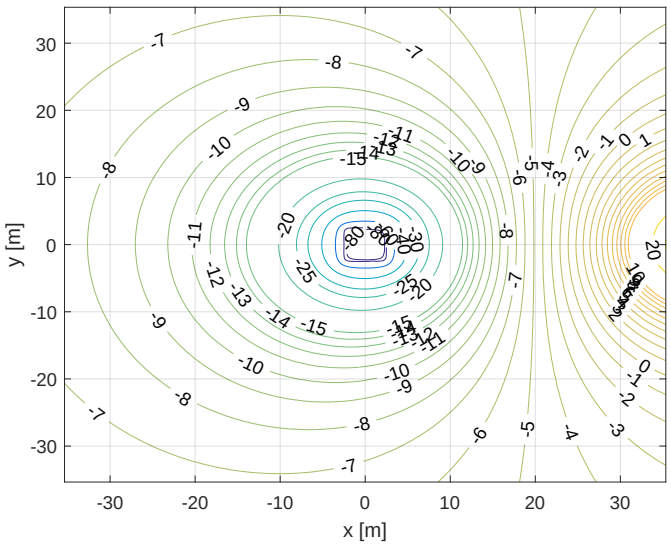

Figure 5. Percentage error of R_{ES} for scenario 1 ($d_C = 40\ m$), according to the position of the voltage probe.

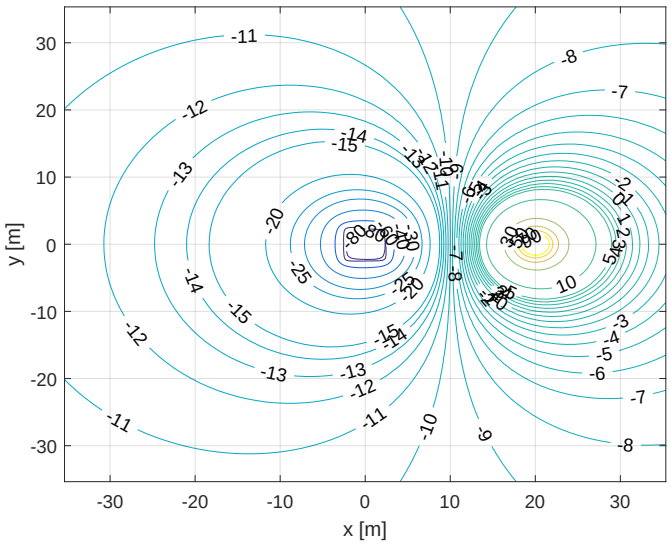

Figure 6. Percentage error of R_{ES} for scenario 2 ($d_C = 20\ m$), according to the position of the voltage probe.

of placing the voltage probe on the opposite side of the ES with respect to the auxiliary current electrode should be avoided.

From a practical point of view, errors lower than 20% could be considered acceptable, provided that the conditions reported by standards for the observance of permissible touch voltages are largely satisfied [1], [21].

IV. FIELD MEASUREMENTS

In order to provide practical examples of the issues reported in section II, the resistances to earth of 19 MV/LV substations in urban context were measured with the FPM.

Here, as an example, the field measurement that highlights the effect of buried metallic parts in the test area is provided.

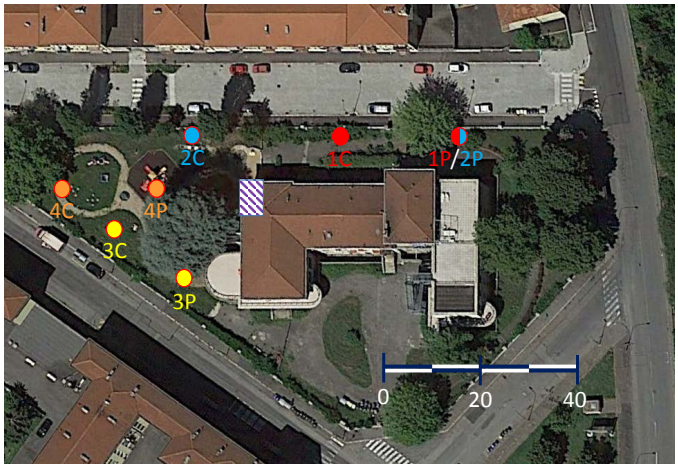

Figure 7. Satellite image of the field measurement site provided by Google Earth. The circles represent the location of auxiliary electrodes. The numbers identify the test number, the letters C and P the current and voltage electrodes, respectively.

Table III
MEASUREMENT RESULTS

Test number	d_C	d_P	[Ω]
1	23	38	3.3
2	14	38	0.42
3	30	24	0.96
4	38	19	4.82

A. Measurement description

A satellite image of the field measurement site is reported in Fig. 7. For confidentiality issues, any geographical references and labels were deleted.

A soil resistivity of $250\Omega m$ was measured, according to the Wenner four-electrode configuration method.

To measure R_{ES}, a 3 terminal ground resistance tester, specifically designed for FPM, was used.

The ES of the substation under test is formed by a ground ring electrode with a diameter of 5 m, buried at 0.75 m from the soil surface. Its maximum extension d is 5 m.

In Fig. 7, the MV/LV substation is highlighted with purple lines, while the location of auxiliary electrodes is reported with colored circles. To evaluate how the position of current electrode C and voltage probe P affects the measurement, four different tests were done. The number near the circles identifies the test, the letters C and P stand for current electrode and voltage probe, respectively.

B. Measurement results

The distances of auxiliary electrode from the MV/LV substation and the values of the resistance R_{ES} measured in the four tests are reported in Table III.

The set of conditions 1, required by EN 50522, was not completely respected. As often happens, the useful area to bury the electrodes was too small, due to the presence of streets and buildings.

As shown in Table III, the position of auxiliary electrodes considerably affects the results. Minimum and maximum values of R_{ES} differ for more than 90%.

In test 2 and 3, the voltage probe was intentionally placed over the MV cable feeding the substation. The low values of R_{ES} are probably due to the presence of bare conductors interconnected with the ES under test, buried together with the power cables, as shown in paragraph II-B.

V. CONCLUSION

In this paper, theoretical considerations and practical examples of issues that can affect the earth resistance (R_{ES}) measurement carried out through the Fall of Potential Method (FPM) in urban contexts were provided.

In order to quantify the error caused by an erroneous positioning of current electrode and voltage probe, a parametric analysis was carried out by Comsol Multyphisics, a commercial software based on Finite Element Method.

A comparison between the criteria suggested by EN 50522 and IEEE Std. 81 is carried out. According to the simulation results, the second one allows lower errors, even if the position of the voltage probe should be accurately chosen. In urban areas, characterized by the presence of buildings and tarmac, the fulfillment of this condition could be very difficult and, for this reason, the authors suggest to bury fixed current and voltage auxiliary electrodes for all the new MV/LV substations. In this way, periodic measurements could be carried out simply and accurately throughout the installation life.

If the criterion suggested by EN 50522 is adopted, for a given distance from the Earthing System (ES), it is more convenient to place the voltage probe not along the direction that connects the ES with the current electrode, due to the non symmetric electric potential profile, but along a perpendicular direction.

Particular care should be devoted to analyze situations in which, due to the presence of buried metallic conductors, important errors could be committed in the earth resistance evaluation.

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