A Comparative Review of the Methodologies to Identify a Global Earthing System

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

***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. Despite that, Standards do not provide any official practical guidelines for its identification. The official classification of GES areas would lead to a simplification of the design and verification procedures of MV/LV substations grounding systems, with associated economical savings for both Distribution System Operators (DSOs) and MV users. To overcome this regulatory vacuum, several teams of researchers proposed methods to identify the presence of a GES.**

In this paper, the main methods developed to identify a GES are presented. The different methodologies are applied to a real urban scenario and compared.

***Index Terms*—Electrical safety, global earthing system, grounding, identification method, indirect contacts, MV distribution system, power distribution faults, power system faults.**

I. Introduction

The international and European standards IEC 61936-1 [1] and EN 50522 [2] define a Global Earthing System (GES) as an "equivalent earthing system created by the interconnection of local Earthing Systems (ESs) that ensures, by the proximity of the earthing systems, that there are no dangerous touch voltages". The same standards explain that "Such systems permit the division of the earth fault current in a way that results in a reduction of the earth potential rise (EPR) at the local earthing system. Such a system could be said to form a quasi-equipotential surface" and that "the existence of a global earthing system may be determined by sample measurements or calculations for typical systems. Typical examples of global earthing systems are in city centers, and urban or industrial areas with distributed low- and high-voltage earthing".

In the definition, three important concepts are expressed: interconnection, proximity and quasi-equipotentiality [3], [4]. From a practical point of view, it can be said that GES has two main effects:

- a fault current distribution among the interconnected ESs;
- a smoothing of the ground potential profile, so that no dangerous touch voltages occur.

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In the last decades, several experiments were carried out to a better comprehension of these phenomena.

In particular, about the first effect, an analytical model that computes current distribution among the interconnected ESs was developed and applied to different test cases. According to the simulation results, the main factors which influence the fault current distribution are the presence of bare buried conductors, the presence of LV neutral conductors, the per unit length resistance of the cables sheaths and the number of interconnected MV/LV substations [5], [6], [7], [8].

Moreover, currents measurements were conducted during a real MV single line to ground fault (SLGF) to evaluate the effects of the ESs interconnection by experience [9], [10], [11], [12], [13].

Another important factor, which should always be considered, is the connection of the MV cables sheaths to the ground-grid of the HV/MV substation; in fact, besides modifying the MV fault current distribution, this interconnection can produce dangerous touch voltages in the MV grid when a fault on the HV network occurs as well [14], [15].

Similarly, for the evaluation of the second effect produced by a GES, field measurements were carried out to characterize the different types of extraneous conductive parts (such as, for example, water and gas pipes) that can be buried in urban areas [16], [17], [18]; the effects of these parts on the ground potential profile were analyzed by an analytical model, based on the Maxwell's subareas method [19]. According to the simulation results, a significant smoothing of the ground potential profile occurs only if buried conductors are widespread and connected to the MV grounding network. If metallic parts are widespread but not interconnected with grounding systems, their effect is negligible. An example of important contribution is provided by distributed LV neutral grounding [20], [21], [22].

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, as shown in a previous work of the Authors' [23].

The identification and official classification of GES areas would lead to a simplification of the design and verification procedures of MV/LV substations grounding systems, with associated economical savings for both Distribution System Operators (DSOs) and MV users. In fact, according to EN 50522, if an ES become a part of a GES, no field measurement to determine soil characteristics, EPRs or touch voltages is required [2].

In this paper, the main methods that have been developed in order to identify a GES are presented. Strengths and weaknesses are emphasized. When possible, the methodologies are applied to a real urban scenario, potentially candidate to be defined as a portion of GES. Moreover, to better evaluate the accuracy of the methods, the maximum EPR for each of the considered MV/LV substations was computed by a dedicate software and used to evaluate if dangerous voltages can appear in case of SLGF.

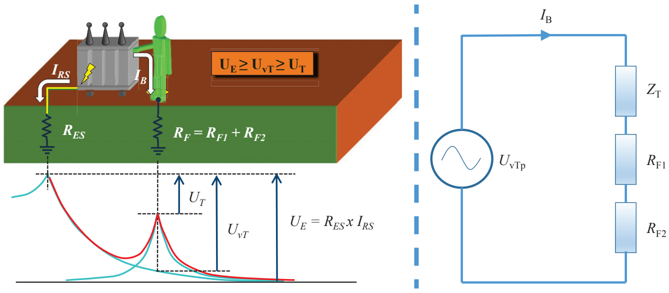

Figure 1. Increment of the permissible EPR (U_E) due to the earth surface potential profile and additional resistances. I_B is the current flowing through the human body, Z_T is the total body impedance, R_{F1} is the resistance of the footwear, R_{F2} is the resistance to earth of the standing point.

II. Methods to identify a GES

A. Ellipse Method

This methodology was developed by the main Italian DSO, Enel Distribuzione S.p.A. (now e-distribuzione), and consists of 6 steps [24], [25]:

1) given a geographical map of the urban area under investigation, a circle with radius equal to 150 m is drawn at the center of each MV/LV substation;
2) an ellipse characterized by a major and minor axis of respectively 1000 m and 500 m is superimposed;
3) if 10 MV/LV substations are included by the ellipse and interconnected according to the in-out scheme, they are selected;
4) for the selected group, the tangent lines to the circles of the more peripheral MV/LV substations are drawn. In this way, an area with a density of about 25 MV/LV substations for km^2 can be defined;
5) the position of the ellipse is varied and the previous steps are repeated;
6) the union of the adjacent areas and of the ESs immediately outside its edge (far less than a quarter of the minimum diagonal of the area) forms a GES.

The ellipse method is based on the DSO's practical knowledge and takes into account only the density of MV/LV substations (D_S) in a geographical area. No rationale was provided to justify the method. Other factors that significantly influence the two GES effects (i.e. distribution of the fault current and equipotentialization of the area), such as the effective cable length between two consecutive substations, the sheath resistance per unit length or the resistance to earth (R_E) of the ESs, are neglected [6].

B. Desmedt Method

A Belgian team proposed an interesting methodology to assess the presence of a GES in a distribution system with low impedance neutral earthing [26], [27].

According to this method, a necessary but not sufficient condition is that at least 20 ESs have to be interconnected through the MV cable shields and/or other protective conductors. In addition, to certify the presence of a GES, at least one of the following conditions shall also be verified:

1) the cable lengths, in m, are not greater then L_{Max} (1);
2) at least 1 km of cables with earthing effect is involved and the mean length of each part of cable without earthing effect does not exceed L_{Max} (1).

Where the maximum length L_{Max} is to be computed by means of equation (1):

$$L_{Max} \leq 500 \cdot \frac{S_m}{16 \quad (mm^2)} \tag{1}$$

where S_m is the weighted average cross-sectional area of the protective conductors, in mm^2.

In the methodology development, the maximum permissible EPR is considered twice the value of the permissible touch voltage as suggested by EN 50522 [2]. In fact, as shown in Fig. 1, the prospective touch voltage is just a portion of the EPR. Moreover, additional resistances were taken into account to determine the prospective permissible touch voltage U_{vTp}, according to EN 50522 (Annex B) [2]. As shown in Fig. 1, the resistance of the footwear R_{F1} and the resistance to earth of the standing point R_{F2} are in series with the total body impedance Z_T.

An extensive research activity is at the root of the proposed formulation, which allows a fast and simple evaluation. These qualities are probably the main strenghts of the Desmedt method.

Vice-versa, the weakness is that this method cannot be used for systems with a different neutral earthing type.

C. Fickert Method

This method was proposed by an Austrian research team and it is based on the results of touch and step voltages measurements campaigns [28].

The tests were carried out in different scenarios. In particular, a substation and two MV overhead line terminal towers were selected in a rural area; furthermore, the measurements were repeated inside and outside a small village.

The maximum values of the ratio between the measured touch voltages and the fault current are reported in Table I. Among the considered cases, very small touch voltages were found in any of the scenarios, with the only exception of the measurements in the MV overhead line terminal towers.

Table I
RATIOS BETWEEN THE MAXIMUM TOUCH VOLTAGES AND THE FAULT CURRENT.

Scenario	[V/kA]
Rural area / substation	14
Rural area / MV overhead terminal towers	700
Small village / center	10
Small village / suburb	90

One of the main conclusions of the paper is that GESs shall have an equivalent earthing impedance below 10 mΩ, considered as the ratio between the touch voltage and the earth fault current. In other words, for each kA of fault current, the touch voltage increase by 10 V.

Taking 80 V as the maximum permissible touch voltage (as suggested by EN 50522 when the duration of current flow is longer than 10 s), and considering the GES equivalent earthing impedance cited above, the Authors suggest 8 kA as the maximum value of the SLGF current that guarantees that the permissible touch voltage limit is respected [2]. However, they recommend to carry out real current injection tests for typical and critical fault locations in order to classify a given grounding situation.

According with the Authors, also small villages can potentially be defined as a GES.

The fragility of the method seems to be in the low number of the carried out measurements. In fact it is not clear if the sample investigated can be considered representative.

D. Campoccia Method

A research team affiliated with the University of Palermo (Italy) proposed simplified circuital models to compute the EPR for 3 fault events: SLGF, Double Ground Fault (DGF) and SLGF on the HV side of the HV/MV station [29].

The models are approximated but it can be proved that the errors are not significant if the following conditions are met:

1) the resistance to earth R_E of MV/LV substation ESs can be considered the same;
2) the distance between two consecutive substation is approximately equal;
3) the presence of metallic elements interconnecting the earth electrodes of the substations but not under the control of the distribution companies (like water and gas lines) can be neglected;
4) the earth resistances of all the earth electrodes of the LV installations, even if connected to the earth electrodes of the substations included in the GES can be neglected.

For the sake of brevity, only the SLGF case is reported here. With reference to the electrical circuit of Fig. 2, the EPR of the faulted substation can be computed from eq. (2).

$$U_{E,H} = \frac{R_E \cdot Z^a_{E,H} \cdot Z^b_{E,H}}{R_E \cdot Z^a_{E,H} + R_E \cdot Z^b_{E,H} + Z^a_{E,H} \cdot Z^b_{E,H}} \cdot I_{F1} \quad (2)$$

where:

- I_{F1} is the SLGF current;

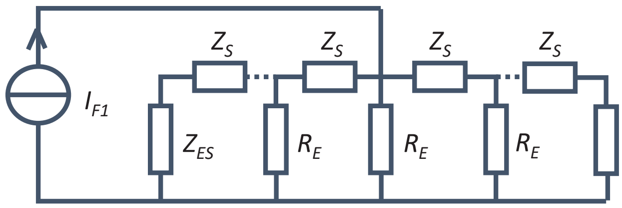

Figure 2. SLGF circuit model. The impedance Z_{ES} is the earth impedance of the HV/MV station; R_E is the average value of the MV/LV substation earth impedance; Z_S is the average value of the metal sheaths impedance.

- R_E is the earth resistance of each MV/LV substations;
- $Z^a_{E,H}$ and $Z^b_{E,H}$ are the driving-point impedances of the metal sheaths calculated according to [30].

Once the EPRs are computed thanks to the simplified models, according to the Authors it is possible evaluate the "*Global Safety*" of the interconnected ESs. A GES can be certified if the minimum requirements for interconnection of LV and HV ESs with regards to indirect contact (CENELEC HD 637 S1) are fulfilled [29] for all the considered fault types.

The results of the calculation provide useful indications on the behavior of GES in different fault conditions and can be used to investigate on which elements can have influence on Global Safety.

The more the conditions described above are met, the better the model works. However, real MV networks are quite complex systems and it is not guaranteed that the assumptions can always be accepted.

E. Parise Method

Another Italian team affiliated with the University of Roma "La Sapienza" proposed a method based on field measurements [31]. In particular, touch and step voltages measurements with auxiliary current electrodes at reduced distance are required [32], [33], [34].

This test can be a valid tool to evaluate the efficacy of ESs in high densely populated areas or in cases where the extension of the ES is large. In fact, in these areas, the evaluation of the EPR for the observance of the permissible touch voltage is not simple. According to the *Fall-of-potential method* given in the international standard EN 50522 (Annex L) [2], the distances between the voltage probe and the earth electrode under test must be at least 4 times the maximum dimension. In practical cases, it is quite difficult to fulfill this condition. The *auxiliary current electrodes method* allows a conservative evaluation of the touch voltage. The higher is the number of auxiliary electrodes, the lower is the error of the measures [32].

The Authors assert that this method can be adopted to identify a GES as well: in a GES, the touch/step voltages measurements do not significantly change if one or more auxiliary current electrodes are adopted [31].

The weakness of the method lies in its potentially being time and money consuming. If adopted, extensive field mea-

Table II
TYPICAL CHARACTERISTICS OF THE MOST COMMON MV CABLES IN THE NETWORK.

Quantity per unit lenght	Cross section [mm^2]		
	95	150	185
phase resistance [Ω/km]	0.320	0.206	0.164
sheath resistance [Ω/km]	1.15	0.73	0.73
phase - sheath capacitance [μF/km]	0.238	0.277	0.300
usage in the network [%]	8	61	26

surement should be carried out and the GES benefit would be scaled down.

III. METHODS APPLICATION AND COMPARISON

The methods described in the previous section are here applied to the feeder of a real urban network reported in Fig. 3. For confidentiality issues, any geographical references and labels were deleted.

The grid rated voltage is 22 kV. The system is operated with isolated neutral and the SLGF current computed by the DSO is 284 A. The permissible touch voltage U_{TP} is 220 V.

A disconnector keeps the phases interrupted (not the cables sheaths, which are never interrupted) in one of the substations, making the meshed system a radially operating network.

Each MV/LV substation is interconnected to the MV lines according to the in-out insertion scheme.

Fig. 4 reports the distribution of the cable length with respect to the average value.

The considered network is almost totally composed of underground cable lines. The characteristics of the most common cables used in the MV system (covering globally 95% of the network) are reported in Table II. In the selected MV line, only 185 mm^2 cables are used.

For all the MV/LV substation, ESs are formed by a grounding ring buried at 0.75 m from the soil surface. The local Resistances to Earth ($R_{E}s$) are not available and therefore a typical value of 5 Ω was considered for all the ESs.

No bare conductors were buried together with the power cables; the interconnection among the ESs of the MV/LV substations is made by MV cable sheaths only.

To limit the problem of exported dangerous voltages in case of SLGF on the HV side, an insulating joint between the MV cable sheaths and the earthing system of the HV/MV station is placed.

In each of the following subsections, one of the methods for the identification of GESs is applied with the exception of "Parise Method", which cannot be tested because measurements are required.

To estimate the accuracy of the methods, a SLGF was simulated in each MV/LV substation of the system by a dedicated software (from this point on "reference model") [6]. For each of the MV/LV substations, the maximum EPR, EPR_{Max}, among the different simulations was evaluated, varying the position of the SLGF (Fig. 5, green line with circle

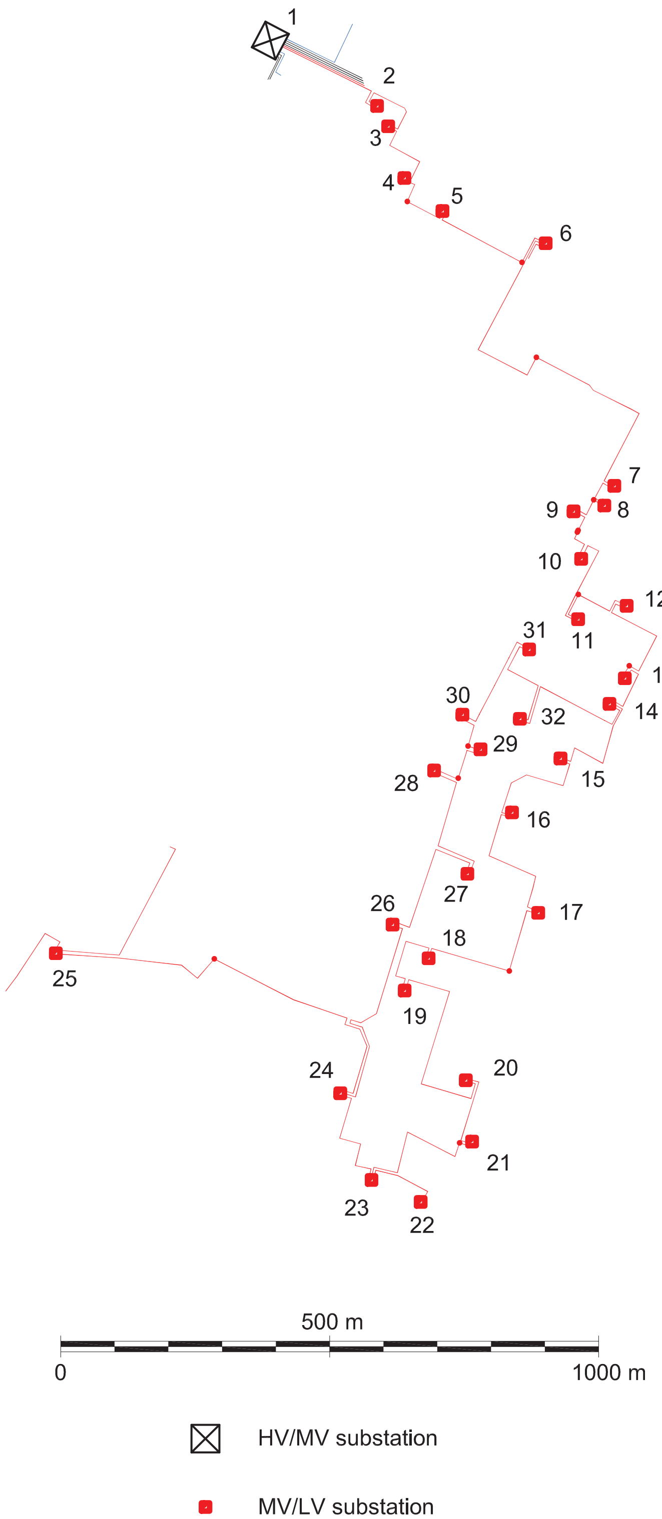

Figure 3. Comparison among the methods: the considered MV line.

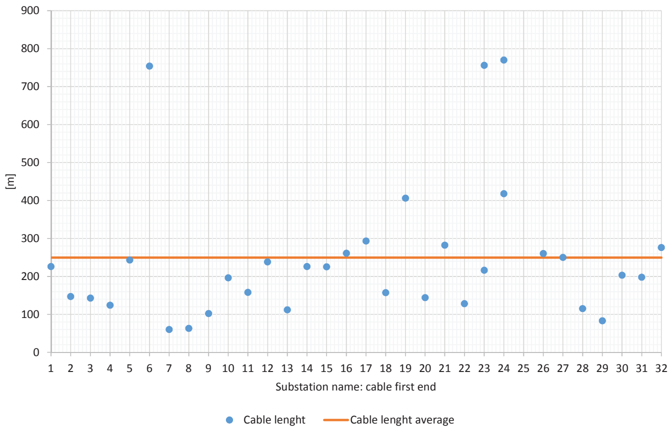

Figure 4. Campoccia method: distribution of the cable length with respect to average value.

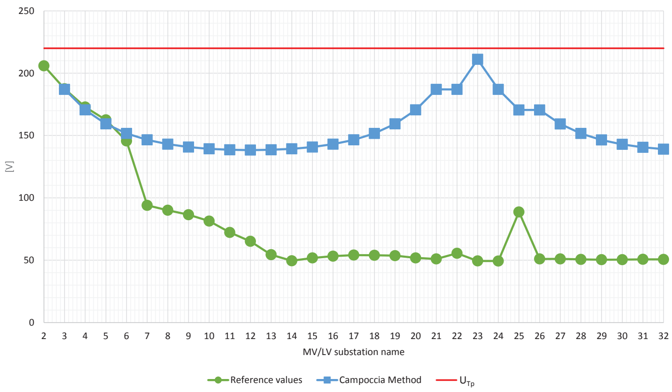

Figure 5. Comparison between the permissible touch voltages and the maximum EPRs computed by both the reference model and Campoccia method for the considered case study.

markers). Considering U_{Tp} as safety threshold, it was assumed that a MV/LV substation can be part of a GES if condition (3) is verified:

$$EPR_{Max} < U_{Tp} \tag{3}$$

Notice that condition (3) is stricter than the requirement provided by Condition C2 of EN 50522[1]. This was an authors' choice, for the sake of safety.

A. Ellipse Method

The circles and ellipses required by the method are superimposed to the plan view of the considered MV line, Fig. 6. In the same figure, on the right, the GES resulting by the method is emphasized by the blue hatch.

According to this method, several MV/LV substations (25/31) could be declared part of a GES. The remaining substations are instead not included in the GES because their density is lower than the minimum required.

[1]EN 50522, section 5.4.2, condition C2: "permissible values are considered to be satisfied if the earth potential rise, determined by measurement or calculation does not exceed double the value of the permissible touch voltage.

This result partially disagrees with the suggestions obtained by the reference model. As shown in Fig. 5, the computed EPR (green line with circle markers) is smaller than U_{Tp} (red line) for all the considered substations, which therefore have rights to become part of a GES. However, it is important to highlight that the excluded MV/LV substations are the ones that present the higher EPRs. This proves that density of MV/LV substations in a geographical area is an important parameter, even if others factors should be taken into account. In fact, if the substations 1-6 present quite high EPRs, substation 25 does not have particular issues that prevent its inclusion into a GES.

The main critical point of this method is the fact that a great importance is given to the geographical layout of the MV/LV substations. In fact, if MV/LV substations were arranged in a different layout, the MV network characteristics being equal (same cable lengths, etc.), the results obtained from the ellipse method would be completely different. However, this difference cannot be justified considering that the influence of a typical MV/LV substation ES is significant only within 4 times its maximum extension (i.e. about 40 m if it is considered isolated [2]). Therefore, even if the MV/LV substations were closer to the GES area, significant modification of the ground potential profile would not be necessarily obtained.

B. Desmedt Method

This method was developed for a system with low-impedance neutral earthing [26]. However, it was applied to the studied scenario as well.

As the number of interconnected substations is 31 (the minimum requirement is 30) and the condition of eq. (1) is fulfilled (L_{Max} = 781 m), all the considered ESs can be declared GES, in accordance with the suggestion provided by the reference model.

Due to its simplicity and speed, this method should be adopted as reference.

C. Fickert Method

According to the Authors, the maximum fault current value that verifies the observation of the permissible touch voltage is 8 kA, which is greater than the SLGF current computed by the DSO (i.e. 284 A). Consequently, according to this method, all the substations form a GES, in accordance with the indication provided by the reference model.

D. Campoccia Method

The Authors of this method proposed three simplified circuit models in order to consider the main fault current events. Here, for the sake of brevity, only the SLGF case analysis is carried out.

The method allows to compute the EPR by the calculation of the driving-point impedances of the metal sheaths, on the base of the formulas reported in [30]. Since these were developed considering a finite chain without branches, it was necessary to make some approximations to use it in a real MV network, which is weakly meshed and where laterals are present.

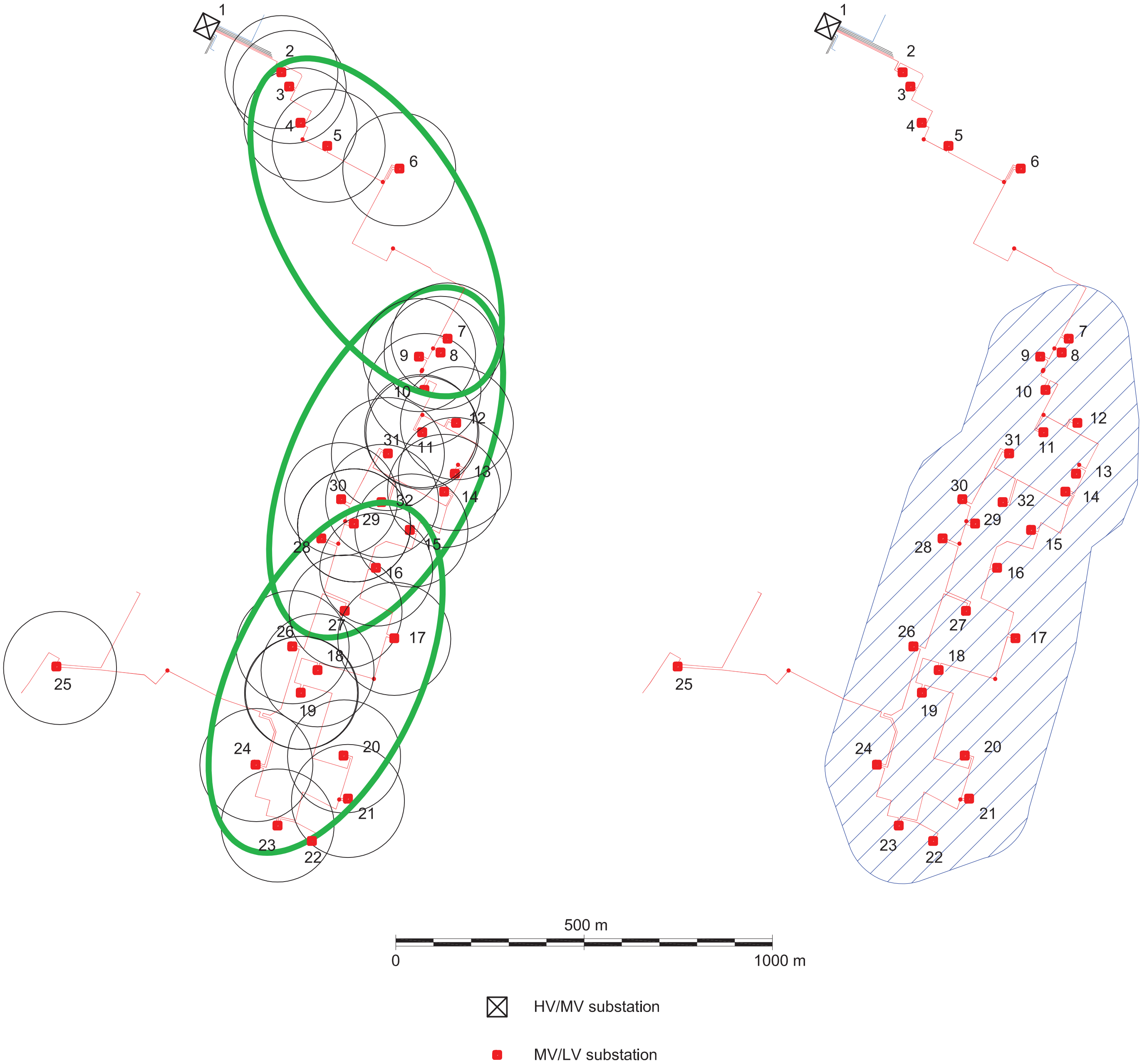

Figure 6. Ellipse method: an application example.

Moreover, since these formulas require the interconnection between the MV cable sheath and the ES of the HV/MV substation, which is not present in the considered case study, the EPR for the first MV/LV substation (number 2) could not be calculated.

Among the conditions that should be verified to use the method without a significant error, the first two are probably the most stringent: the R_E of MV/LV substation ESs could be considered the same; the cable length between two consecutive substations is approximately equal.

Even if the R_{ES} are not available and a typical value was assumed, the comparisons between the real cable lengths and its average value is shown in Fig. 4. Although a certain variability can be noticed, it is not possible to stipulate a-priori if the requirement is met. In fact, no details about the variability that keeps the error under an acceptable threshold are given.

According to the position of the faulted MV/LV substation, the driving-point impedances of the metal sheaths $Z^a_{E,H}, Z^b_{E,H}$ varies in the range $1.1 \div 2.8\ \Omega$. For the considered fault current (284 A), a variation of the EPR in the range $135 \div 188$ V can be computed by eq. (2).

In Fig. 5, the comparison between the EPRs calculated by the Campoccia Method (blu line with square markers) and the reference model (green line with circle markers) is reported. Both the models indicate that EPRs are smaller than U_{Tp} and, therefore, that the whole feeder could become part of a GES. However, two observations shall be done: first, the EPRs computed by the reference model in substations 3, 4 and 5 is slightly higher than those computed according to the Campoccia Method; second, far from the HV/MV substation, the Campoccia Method provides results that seems too conservative.

In conclusion, even if this method can be useful for a general evaluation of the MV line aptitude to become part of a GES, it cannot be used for an accurate computation of the fault current distribution as it requires just few input parameters. Dangerous scenarios, characterized for example by anomalous distances between two consecutive substations, could not be detected.

IV. Conclusion

In this paper, the main methods to identify a GES, proposed in literature, were presented and applied to a real urban scenario, possible candidate to be certified as a portion of GES.

The maximum EPR for each of the considered MV/LV substations was computed by a dedicate software and used to evaluate if dangerous voltages can appear in case of SLGF. In this way, the accuracy of the methods can be better appreciated.

Three of the four tested methods certified the presence of a GES for all the considered area, in accordance with the results of the reference software. The Ellipse method however reveals a GES only in the urban districts where the MV/LV substations density is higher. This result is in contrast with the output of the simulations. Even if the excluded substations are mainly the ones that present higher EPRs, these values were not critical.

Each of the methods have some critical points:

- the Ellipse method gives a great importance to the geographical layout of the MV/LV substations. It does not seem to be justifiable, especially as the characteristics of the network (cable properties and lengths, R_E of the MV/LV substations, meshes and interconnections, etc.) are instead not considered at all. Moreover, it seems to be too conservative;
- the Desmedt method is particularly interesting even if it cannot be applied in Italian MV networks, characterized by isolated neutral or resonant earthing. In fact, it was designed for a system with-low impedance neutral earthing;
- the Fickert method is particularly fast only if touch voltage measurements should not be carried out. However, the sample size of touch and step voltage measurements collected by the Authors seems to be not sufficiently numerous to produce a general methodology;
- the Campoccia method is interesting for a general evaluation of the MV line aptitude to become part of a GES; however, it is possible that dangerous scenarios could not be detected. It cannot provide an accurate analysis of the fault current distribution. In fact, the MV earthing network is modeled with only an input value for the distance between two consecutive substations and for the R_E of the ESs. Non homogeneous cases cannot be properly modeled. Moreover, with this method, it is not possible to take into account weakly meshed configurations and laterals, as well as the absence of interconnection with the ES of the HV/MV substation. These aspects caused same problems in the straightforward application to the case study;
- the Parise method, based on touch and step voltages measurements with auxiliary current electrodes, allows a conservative evaluation of the GES safety. Nevertheless, the weakness of the method lies in its potentially being time and money consuming. If adopted, extensive field measurements should be carried out and the GES benefit would be scaled down.

None of the available methodologies have been massively adopted by the Italian DSOs. In fact, in Italy, just few cases of GES are certified. Starting from the main effects of a GES, an innovative approach that goes beyond the limits of the presented methods could be an important step-forward for the GES diffusion.

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