An Analytical Procedure to Identify a Global Earthing System

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***Abstract*—Global Earthing System (GES) is defined by international standards IEC 61936-1 and EN 50522 as an equivalent Earthing System (ES) created by the interconnection of local ESs. Thanks to this interconnection, just a percentage of the total fault current is injected to ground in a single ES, with a significantly reduction of touch voltages in case of fault. If a GES is officially certified, the procedure to verify the effectiveness of an ES can be simplified, with advantages in terms of time and money. Unfortunately, Standards do not provide any practical guidelines to identify a GES. In this work, a methodology is proposed for MV network with the neutral point isolated from ground. A practical example is provided.**

I. Introduction

The Standards EN 50522 and IEC EN 61936-1 define a Global Earthing System (GES) as the *"equivalent Earthing System (ES) created by the interconnection of local earthing systems that ensures, by the proximity of the earthing systems, that there are no dangerous touch voltages"* [1], [2].

The interconnections among ESs of MV/LV substations, trough for example MV cable sheets or LV neutral conductors [3], [4], have mainly two effects:

- a distribution of the fault current between grounding electrodes (of the faulty substation and of the neighbouring ones) and MV cables sheaths [3], [5], [6];
- a smoothing of the ground surface potential profile, reducing the hazardous voltage gradients [4], [7], [8].

If GESs are officially certified, the procedures to verify the effectiveness of an interconnected ES are significantly simplified, since visual checks and continuity measurements can be considered enough. If not, the measurements of the resistance to earth or of touch voltages shall be performed [1]. In urban and industrial areas, where typically GESs can be found, the measurement of the resistance to earth can be affected by many issues and if the technicians are not sufficiently expert, results may not be reliable [9]. Vice-versa, the measurement of touch voltages is quite money consuming and requires particular instruments. Moreover, it can be dangerous for workers since high touch voltages can be established.

Unfortunately, Standards do not provide any practical guidelines to identify GESs, which for this reason are rarely certified by Distribution System Operators (DSOs). To fill this gap, in the last years, many researchers developed methodologies for their identification [10]–[16]. These methodologies present some inconvenient, or because are not sufficiently accurate or because are quite cumbersome, or simply because they refer to MV networks with particular characteristics. This work is an additional contribution to achieve this goal. Considering MV systems with the neutral point isolated from ground, practical guidelines are proposed.

The first step in GES identification procedure is the definition of the safety level that a GES should guarantee, as discussed in section II.

The second is the formalization of the procedure, i.e. the practical actions that DSO could accomplish to certify the presence of a GES. The methodology proposed in this work is focused on the distribution of the fault current, which is the most significant effect of a GES according to simulation and measurement results [3], [6], [7]. The better the interconnection among the ESs, the more effective the distribution of the fault current. A parameter to evaluate the level of interconnection among the ESs is the reduction factor r [1]. For an underground MV system, it can be defined as the ratio of the current injected by the faulted substations and the total fault current [6]. Several models in literature were developed to analytically compute the reduction factor. Some of them are accurate but require to implement the MV network [3], [5]. The methodology proposed in this work is based on an analytical formulation of the reduction factor, developed for MV systems with the neutral point isolated from ground [17].

Algebraic manipulations were done to transform this analytical expression in a form more appropriate for guidelines, as better explained in section III.

The proposed guidelines are indeed described in section IV, as well as the rationale on which they are based. Finally, as an example of application, they are applied to a real case study in section V.

II. Safety level required for a GES

For the proposed guidelines, it was assumed that a GES system shall guarantee the condition in eq. (1):

$$EPR \leq U_{Tp}(t) \tag{1}$$

where:

- EPR is the earth potential rise;
- $U_{Tp}(t)$ is the permissible touch voltage, which is a function of the duration of the MV Single Line to ground Fault (SLGF), in accordance with Fig. 1.

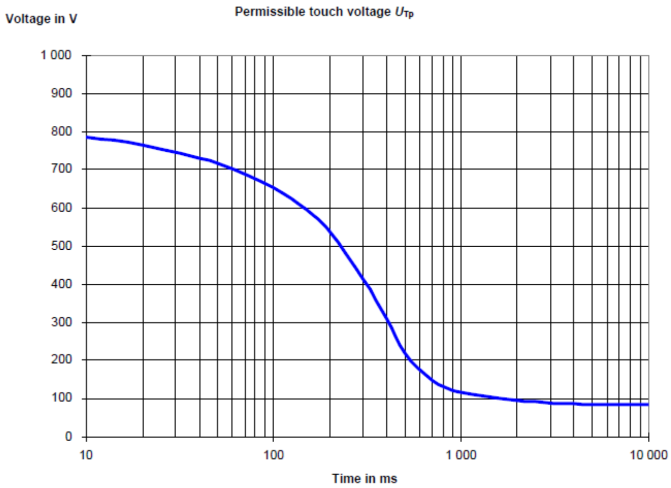

Figure 1. CEI EN 50522 - Permissible touch voltage in HV and MV systems.

Table I
CEI EN 50522 - MINIMUM REQUIREMENTS FOR INTERCONNECTION OF LOW VOLTAGE AND HIGH VOLTAGE EARTHING SYSTEMS BASED ON EPR LIMITS.

Type of LV system[(a, b)]		*EPR Requirements*		
		Touch Voltage	*Stress Voltag*[(c)]	
			Fault duration $t_f \leq 5$ s	*Fault duration* $t_f > 5$ s
TT		*Not applicable*	EPR ≤ 1 200 V	EPR ≤ 250 V
TN		*EPR ≤ F · U_{Tp}* [(d, e)]	EPR ≤ 1 200 V	EPR ≤ 250 V
IT	*Distributed protective earth conductor*	*As per TN system*	EPR ≤ 1 200 V	EPR ≤ 250 V
	Protective earth conductor not distributed	*Not applicable*	EPR ≤ 1 200 V	EPR ≤ 250 V

(a) For definitions of the type of LV systems, see HD 60364-1.
(b) For telecommunication equipment, the ITU recommendations should be used.
(c) Limit may be increased if appropriate LV equipment is installed or EPR may be replaced by local potential differences based on measurements or calculations
(d) If the PEN or neutral conductor of the low voltage system is connected to earth only at the HV earthing system, the value of F shall be 1.
(e) U_{Tp} is derived from Figure 4.

NOTE The typical value for F is 2. Higher values of F may be applied where there are additional connections of the PEN conductor to earth. For certain soil structures, the value of F may be up to 5. Caution is necessary when this rule is applied in soils with high resistivity contrast where the top layer has a higher resistivity. The touch voltage in this case can exceed 50 % of the EPR.

The condition in eq. (1) is similar to the condition C2 reported in EN 50522 for the observance of permissible touch voltages, which requires that "*The earth potential rise, determined by measurement or calculation does not exceed double the value of the permissible touch voltage*" in accordance with Fig. 1 [1]. The only difference is the value of the multiplication coefficient of U_{Tp}, which is more severe in eq. (1). The reasons for this choice are two. First, it seems reasonable that GESs provide more safety guarantees than a single local ES, since in this case the maintainability procedures are skin-deep. In fact, to verify the adequacy of an ES that is part of a GES, it is sufficient to check its interconnection with the earthing network; more accurate analyses are not necessary. Secondly, since GESs can be typically found in urban scenarios where LV and MV ESs co-exist, it is necessary to consider the transferred potentials according with the EN 50522 [1]. Even if LV earthing systems cannot modify the earth potential profile when a MV fault occurs [7], dangerous touch voltages can be impressed on them. Moreover, for TN systems, it is important to stress that a MV fault increases the voltage of connected ECPs on the LV side. The practice recommended by EN 50522 to avoid transferred potential from HV systems to LV systems is the interconnection of all HV with LV ESs. This method is admitted by EN 50522 if the requirements in Table I are satisfied [1]. For TN systems, if PEN or neutral conductor of the LV system is connected to earth only at the MV ES, the suggested value of the multiplication coefficient of U_{Tp}, F, is 1 (note (f) of Table I). The safety condition reported in eq. (1) is therefore in line with this requirement. If a TN system with these characteristics became part of a GES, the condition of Table I would be respected.

III. NEW CONDITIONS TO IDENTIFY A GES

Let's consider a MV network with the neutral point isolated from ground and feeders composed by MV cables only. Given a MV/LV substation, S_f, whose ES is interconnected through MV cable shields to the ESs of other N MV/LV substations, S_i, (with $N \geq 10$), the conditions to consider S_f part of a GES can be expressed in terms of its resistance to earth R_E, as explicated in the following sections.

A. First condition

Theoretically, it is possible to use the analytical expression of the factor r presented in the paper [17] to verify the fulfillment of eq. (1).

If the characteristics of the MV network and the Single Line to Ground Fault (SLGF) current I_F are known, the EPR for a considered MV/LV substation S_f can be computed according to eq. (2):

$$EPR = R_E \cdot r \cdot I_F \tag{2}$$

where R_E is the resistance to earth of the faulted substation.

Nevertheless, this methodology is not completely effective in practice due to some unsolvable issues. For instance, DSOs cannot use the analytical expression if the ES is still under construction, since the resistance to earth R_E cannot be measured. Moreover, ES designers do not have a reference for the value of R_E that assures that the substation under construction can be included in a GES.

For this reason another formulation that overcomes these issues was developed. Considering the formula to compute r presented in the paper [17], from eq. (1) and eq. (2), after some mathematical manipulations, it is possible to compute R_{EM}, the maximum value of R_E that ensures the fulfillment of eq. (1) by eq. (3).

$$R_{EM} = \left(\frac{100 \cdot U_{tp}}{K_i \cdot I_F} \right)^5 \tag{3}$$

where K_i is the interconnection factor, defined by eq. (4)

$$K_i = R_{Em}^{0.8} \cdot \frac{3}{F_L \cdot k_{i1}} \cdot L^{k_{i2} \cdot c} \tag{4}$$

Table II
c FACTOR.

MV cable cross section	c
$\leq 95\ [mm^2]$	0.34
$> 95\ [mm^2]$	0.3

Table III
k_{i1} AND k_{i2} FACTORS.

Interconnection level of the electrical system	k_{i1}	k_{i2}
Interconnection through LV neutral conductors: a LV cabinet can be fed by the MV/LV substation S_f and, at least, another MV/LV substation.	0.25	0
Interconnection through MV cable shields: the considered MV/LV substation has more than two MV cables in input/output, even if the phases are disconnected.	0.25	0
Interconnection through bare buried conductors: a bare buried conductor, directly in contact with the soil, runs in parallel with the MV cable.	0.5	0
None of the above or unknown interconnections	1	1

where:

- R_{Em} is the average resistance to earth, computed as the mean value of the N substations S_i;
- c is a coefficient, which depends on the MV cable type cross section (Table II);
- k_{i1} and k_{i2} are coefficients, depending on the interconnection level of the earthing network (Table III);
- F_L is a coefficient, which depends on the fault position in the feeder (Table IV);
- L is the corrected length between substations, computed as:

$$L = \frac{L_m + L_{max}}{2} \tag{5}$$

where:
  - L_m is the average of the cable length between substations for the set S_i;
  - L_{max} is the maximum length of the cables that directly interconnect the substation S_f to the set S_i.

Eq. (3) is the upper limit for the resistance to earth. If this condition is fulfilled, the safety level of eq. (1) is verified.

B. Second condition

The maximum value of R_E that ensures the respect of eq. (1) can be computed by eq. (3). If this value is low, the interconnection among ESs is not strong, that is, the faulted substation S_f plays a key role in the injection of the fault current into the earth. The protection against indirect contacts is not guaranteed by the presence of an effective earthing network, as in a GES, but thanks to the performance of a single ES.

Since the goal of the methodology is to identify a GES, a second condition was introduced. The maximum value of the resistance to earth, R_{EM}, shall be bigger than $R_{Lim} = 5\ \Omega$, an arbitrary minimum threshold for R_E.

Table IV
F_L FACTOR.

Position of the considered substation in the MV feeder	F_L
First five substations of the feeder	0.8
Other substations	1.5

IV. GUIDELINES

In this section, an analytical procedure that evaluates if a MV/LV substation can be included in a GES is proposed.

In paragraph IV-A, the requirements that should be verified before using the method are declared and commented. In paragraph IV-B, the methodology is finally presented.

A. Requirements for use

Some requirements shall be verified to use the proposed guidelines:

1) the feeders shall be composed by MV cables only;
2) the neutral point of the MV system shall be isolated from ground;
3) the MV earthing network, candidate to become a GES, shall not have interconnections with HV ESs;
4) the interconnected MV ESs shall be at least 10.

The first condition ensures that the distribution of the SLGF current can be possible. In fact, in the most MV systems with overhead lines, the interconnections among ESs are not present and therefore a GES cannot be certified.

The second condition originates from the characteristics of the network used to carry out the simulations, on which base this methodology was developed [3], [17].

The third condition derives from the fact that SLGF currents in HV systems are considerably higher that in MV systems, and they can produce touch voltages that exceed the permissible ones.

The fourth condition ensures the redundancy of ESs in the protection of people against indirect contacts. Typically, this requirement is always fulfilled in urban and industrial areas.

B. Methodology for GES identification

This method is based on the interconnection properties of the ESs in a MV grid. The following steps are required:

1) to select a MV/LV substation S_f;
2) to select the 10 MV/LV substations S_i (i=1 ...10) that mainly contribute to inject the fault current in S_f (basically, the nearest ones);
3) to characterize the resistance to earth of each MV/LV substation in the set S_i through the procedure presented in paragraph IV-B1;
4) to characterize the interconnections among ESs;
5) to compute the maximum resistance to earth R_{EM} through eq. (3);
6) to compare the calculated R_{EM} with the reference value $R_{Lim} = 5\Omega$, defined in paragraph III-B:
   - if $R_{EM} < R_{Lim}$, the substation S_f cannot contribute to form a GES; a low value of R_{EM} means

that S_f should be able to inject the entire fault current without producing dangerous touch voltages;
- if $R_{EM} \geq R_{Lim}$, the substation S_f can contribute to form a GES; a large value of R_{EM} means that the neighboring substations significantly contribute to leak the fault current;

7) to check that the resistance to earth of the substation S_f respects the condition: $R_E \leq R_{EM}$; this requirement ensures that a GES will be formed by ESs that fulfill a minimum effectiveness level;
8) to repeat the analytical procedure described above for all the MV/LV substations that could form a GES.

An earthing network formed by at least 10 ESs and that meets all the aforementioned requirements is considered a GES. A flowchart of this analytical procedure is provided in Fig. 2 to exemplify the methodology.

1) Local resistance to earth R_E: The local resistance to earth of a substation can be evaluated by applying one of the following methodologies:

- performing experimental measurements, carried out after the disconnection of all the possible interconnections among ESs;
- adopting the empirical and analytical approach proposed in eq. (6):

$$R_E = \frac{R_{Tot}}{k} \tag{6}$$

  where:
  - R_{Tot} is the resistance to earth measured in normal operating conditions, where all the interconnections are active;
  - k is the ratio between the leaked current I_{ES} and the SLGF current. This coefficient can be considered equal to 0.03, if it cannot be measured and any other information is not available. This value is based on the results of analytical simulations and field measurements [3], [5], [6];
- the analytical approach presented in the Annex J.2 of the EN 50522: eq. (7) allows the R_E computation for a ring earth electrode. If the soil resistivity value is not available, it can be assumed equal to 500 $\Omega \cdot m$:

$$R_E = \frac{\rho_E}{\pi^2 D} ln \frac{2\pi D}{d} \tag{7}$$

V. Example of application

The method described in the previous section is here applied to each MV/LV substation (identified by the ID number) in the portion of the real urban network that was used as case study in [17].

A. Computation of the maximum resistance to earth R_{EM}

For the considered MV network, the SLGF current is 284 A and U_{TP} is 220 V, according to the duration of the fault.

For each MV/LV substation identified by the ID number, S_f, Table V reports the input parameters required by eq. (3) and the calculated maximum resistance to earth R_{EM}.

Table V
Application example: input parameters and computed R_{EM}

ID	R_{Em}	F_L	c	k_{i1}	k_{i2}	L	K_i	U_{TP}	R_{EM}
#	[Ω]	-	-	-	-	[m]	-	[V]	[Ω]
2	5	0.8	0.3	1	1	238	70	220	2
3	5	0.8	0.3	1	1	198	66	220	2
4	5	0.8	0.3	1	1	196	66	220	2
5	5	0.8	0.3	1	1	246	71	220	2
6	5	0.8	0.3	1	1	502	88	220	1
7	5	1.5	0.3	1	1	502	47	220	12
8	5	1.5	0.3	1	1	156	33	220	71
9	5	1.5	0.3	1	1	176	34	220	60
10	5	1.5	0.3	1	1	223	37	220	42
11	5	1.5	0.3	1	1	223	37	220	42
12	5	1.5	0.3	1	1	244	38	220	37
13	5	1.5	0.3	1	1	244	38	220	37
14	5	1.5	0.3	0.25	0	263	29	220	136
15	5	1.5	0.3	1	1	238	37	220	38
16	5	1.5	0.3	1	1	255	38	220	34
17	5	1.5	0.3	1	1	271	39	220	31
18	5	1.5	0.3	1	1	271	39	220	31
19	5	1.5	0.3	1	1	328	41	220	24
20	5	1.5	0.3	1	1	328	41	220	24
21	5	1.5	0.3	1	1	266	39	220	32
22	5	1.5	0.3	1	1	503	47	220	12
23	5	1.5	0.3	0.25	0	503	29	220	136
24	5	1.5	0.3	0.25	0	510	29	220	136
25	5	1.5	0.3	1	1	510	47	220	12
26	5	1.5	0.3	1	1	334	41	220	23
27	5	1.5	0.3	1	1	255	38	220	34
28	5	1.5	0.3	1	1	250	38	220	35
29	5	1.5	0.3	1	1	182	35	220	57
30	5	1.5	0.3	1	1	226	37	220	41
31	5	1.5	0.3	1	1	226	37	220	41
32	5	1.5	0.3	1	1	263	39	220	33

B. First check: comparison between the computed R_{EM} and R_{Lim}

Nearly all the MV/LV substations have a R_{EM} greater than R_{Lim}. Therefore, it means that when a SLGF occurs in a substation S_f, the ESs of the near substations inject into the soil a significant part of the fault current.

Just the 5 substations at the beginning of the feeder,near the HV/MV station, do not respect the condition and cannot become part of a GES. This is in agreement with the simulation results [3].

C. Second check: comparison between the resistance to earth of the substation S_f with reference to R_{EM}

For each MV/LV substation that passes the first check, a second comparison is carried out. R_E should be lower than the computed R_{EM}. The resistance to earth of the ESs is considered equal to 5 Ω, as was done in [10].

According to this, the earthing network formed by the ESs of the neighboring substations 7÷32 can be considered part of a GES, since their number is greater than 10.

This conclusion can be evaluated taken into account the EPRs computed through the reference model in [10], and reported in Fig. 3 for the sake of clarity. Even if the computed EPR is always lower than the permissible touch voltage, that is condition in eq. (1) is always fulfilled, the first 5 substations

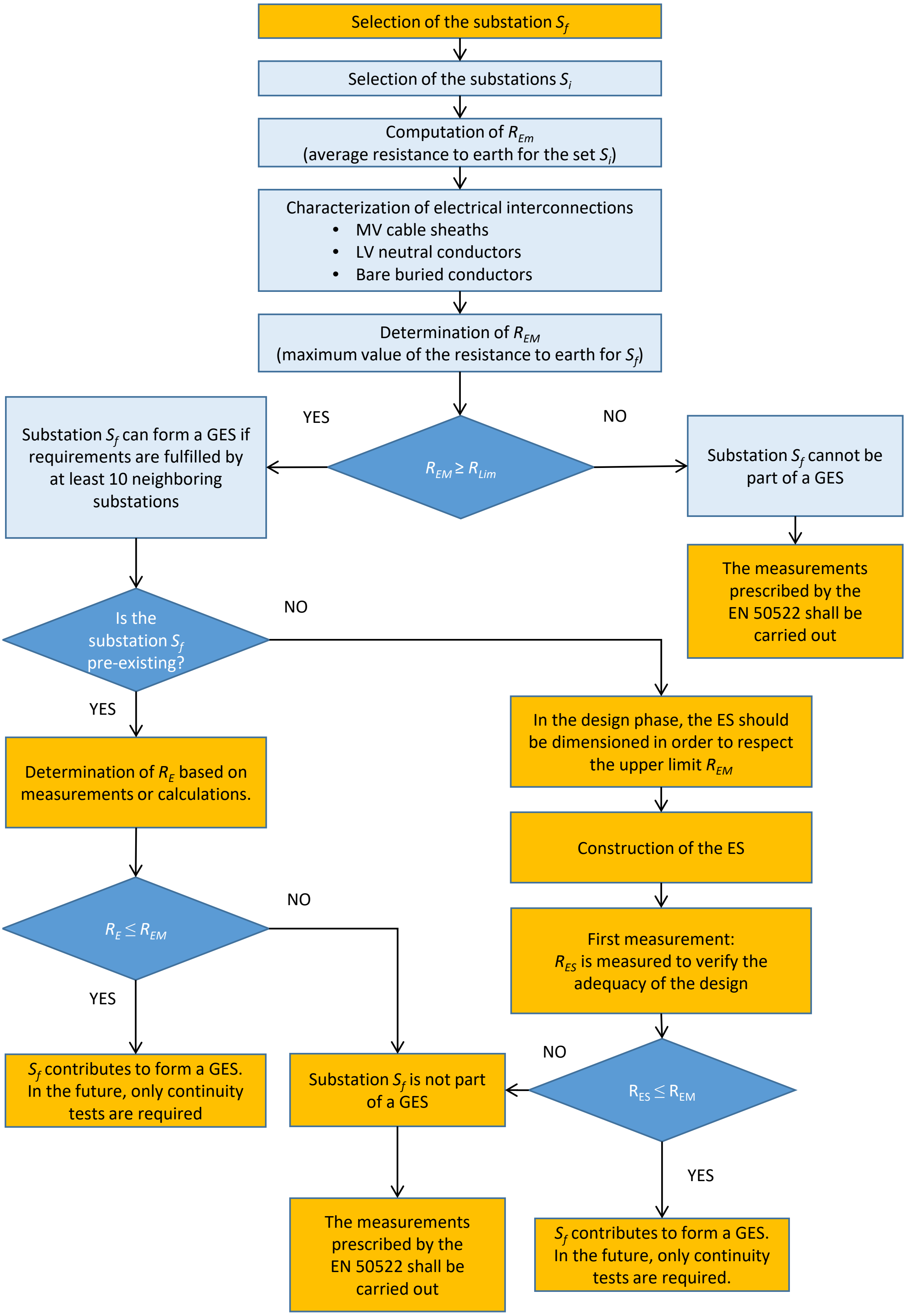

Figure 2. Analytical procedure to certify the presence of a GES.

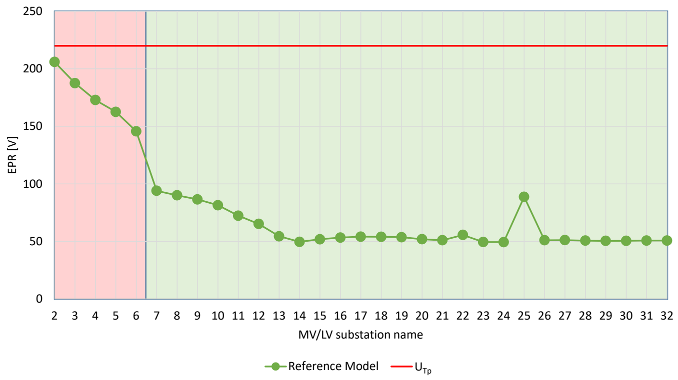

Figure 3. Maximum EPR computed by the reference model and permissible touch voltage for the considered MV feeder. The substations that become part of a GES are in the green portion of the graph. The others in the red one.

present an EPR significantly higher than the others. This can be considered in line with the exclusion of these substations from the GES.

According to this, it is possible to affirm that these guidelines can be an useful tool to identify GESs.

VI. Conclusion

GESs can be the way for DSO and MV Users to simplify the field measurements required by the maintainability procedures, with significant money and time savings.

Unfortunately, since Standards do not provide any practical guidelines to identify GESs, the number of certified GES is quite small. This work wants to be a contribution in the definition of shared procedures to identify GES. In particular, the proposed method refers to underground MV networks with the neutral point isolated from ground.

An example of application was carried out. Moreover, for this example, a comparison with the EPRs computed through an analytical model taken as reference was presented. According to this, it can be concluded that these guidelines can be a valid tool to identify GESs.

The main strengths of the proposed guidelines are:

- the rational beyond each steps derives from the results of simulations or field measurements;
- DSOs can use the methodology both in the maintainability phase as well as in the design phase. ES designers could have a threshold value that ensures that the substation under construction can be included in a GES;
- sophisticated tools are not necessary. A spreadsheet is enough;
- the method was developed considering MV networks with the neutral point isolated from ground. The same approach can be adopted for MV networks with other characteristics, provided that a new expression for the reduction factor r is formulated. This expression is in fact the basis to compute R_{EM};
- they can be considered as a boost for DSOs to improve their knowledge of MV networks. The more details about the MV grid are known, the more likely the earthing network can be certified as a GES. In particular, the information about the interconnections among ESs are particularly relevant.

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