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MV Ground Fault Current Distribution: an Analytical Formulation of the Reduction Factor

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***Abstract*—Global Earthing Systems (GESs) are 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, reducing the risk of electrocution. However, even if several experiments and models proved this effect, the identification and official certification is already a difficult task. If dangerous scenarios caused by a single line to ground fault can be easily evaluated for a specific MV feeder by measurement or analytic models (quite cumbersome to use), operative procedures valid for all the scenarios are not still available. In this work, a simplified formula to compute the reduction factor is presented, as well as its rationale. The proposed formula is easy to use and the results provided are sufficiently accurate, taking into account a desired safety margin. For this reason, it could be a valid tool for Distributor System Operators (DSO) and Certification Bodies and a step forward for the GES identification.**

I. Introduction

The international and European standards IEC EN 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 in the notes 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.

If a GES is officially certified, both MV users and Distribution System Operators could enjoy economical savings since design and verification procedures are simplified for an ES of an MV/LV substation that is part of a GES [3].

Unfortunately, standards do not provide any practical guideline to identify GESs. With the aim of addressing this issue, it is important to focus on the physical phenomena linked with a GES. In the definition, three important concepts are expressed: interconnection, proximity and quasi-equipotentiality [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 [5]–[7];
- a smoothing of the ground potential profile, so that no dangerous touch voltages occur [8]–[11].

In this work, only the first effect will be considered.

For the comprehension of the fault current distribution phenomenon, experimental measurements were conducted during a real MV single line to ground fault (SLGF) [12], [13]. Moreover, the current distribution among the interconnected ESs was studied by specific analytical models, based on the construction and on the resolution of the grid equivalent electrical circuit [5], [14]–[16].

According to the simulation and field measurements results, the portion of the fault current injected into the ground through the ES of the substation in which the fault occurs is just some percent of the total fault current.

A typical index to evaluate the increment of electrical safety due to the fault current distribution is the reduction factor r, defined as the ratio between the current injected to ground through the ES of the substation in which the fault occurs and the total fault current [2], [13].

Several factors influence the fault current distribution, such as the length and the characteristics of MV cables, additional interconnections between ESs made by bare buried conductors or LV neutral conductors, the number of interconnected MV/LV substations, the position and the resistance to earth of the faulted substation, etc. [5].

The models available in literature differ in accuracy and ease of use, according to the number of the considered MV network parameters. If several factors of influence are taken into account, the results are truthful but the tool becomes too complex to be used in an operative context [5]; vice-versa, if simplified hypotheses are adopted, the models becomes easy to manage but not completely reliable [16], [17].

In this work, an innovative simplified model is presented. The objective is to provide a formula to compute the reduction factor r, which can be both accurate and easy to be used.

The model is based on the results of a parametric analysis carried out through one of the complex models available in literature, taken as reference [5].

In this paper, the reference model is shortly presented, as well as the proposed formula and its rationale. Then, the proposed formula is applied to a test feeder and the results are discussed.

Table I
c FACTOR.

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

II. Analytical Formulation of the Reduction Factor

The formula for the calculation of the reduction factor r presented in this work was obtained on the basis of the results of a parametric analysis, carried out by a model of the MV faulted network available in literature [5]. For the sake of brevity, it is called "reference model" (RM) from this point on. The RM requires three steps: first, an equivalent electrical circuit is built for every MV network component, such as, for example, HV/MV substations or MV feeders; then, the blocks representing each element are assembled to set the desired MV distribution system up; finally, the full electrical circuit is solved using the node method to calculate the currents in all branches and the voltages in all nodes [5].

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 $N \geq 10$), it is possible to compute the reduction factor through the Simplified Formula (SF) reported in eq. (1):

$$r = \left(\frac{R_E}{R_{Em}}\right)^{-0.8} \cdot \frac{\frac{3}{F_L \cdot k_{i1}} \cdot L^{k_{i2} \cdot c}}{100} \tag{1}$$

where:

- R_E is the resistance to earth of the considered MV/LV substation S_f, when no interconnections among ESs are present;
- 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 I);
- k_{i1} and k_{i2} are coefficients, depending on the interconnection level of the earthing network (Table II);
- F_L is a coefficient, which depends on the fault position in the feeder (Table III);
- L is the corrected length between substations, computed as:

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

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.

Table II
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	1	1

Table III
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

III. Rationale

In this section, the rationale of eq. (1) is reported. It is organized on the basis of the different factors of influence taken into account.

A. MV cable properties

As proved by the simulation results presented in [5], the largest value of the factor r occurs when:

- the ES of the HV/MV is disconnected from the grounding network;
- the fault occurs in the first MV/LV substation of a feeder;
- the ES of the considered substation S_g is interconnected to only one other ES (there are no additional connections through MV cable sheaths or LV neutral conductors).

In this case, the factor r is a function of the distance between substations, and of the MV cable characteristics (sheath material and cross section) [5]. Fitting the values computed by RM for three different MV cables (their characteristics are reported in Table IV), taken as reference, a simplified formula was developed:

$$r[\%] = 3 \cdot (L_m)^c \tag{3}$$

where:

- c is a coefficient, function of the MV cable cross section (Table I);
- L_m is the average of the cable length between substations.

In the r formulation, the corrected length L defined as in eq. (2) allows to take into account both the characteristic of the considered substation S_f (for which the reduction factor is computed) and the "global" characteristics of the earthing network.

The comparison between the values computed by RM and by the simplified eq. (3) is presented in Fig. 1.

Table IV
MV CABLES.

MV Cable	Cu50	Cu150	Pb95
Phase conductor cross section [mm^2]	50	150	95
Phase conductor resistance [Ω/km]	0.441	0.144	0.222
Sheath material	Cu	Cu	Pb
Sheath mean diameter [mm]	20	26	18
Sheath resistance [Ω/km]	1.15	0.73	1.8
Capacitance between phase conductor and metal sheath [$\mu F/km$]	0.204	0.348	0.297

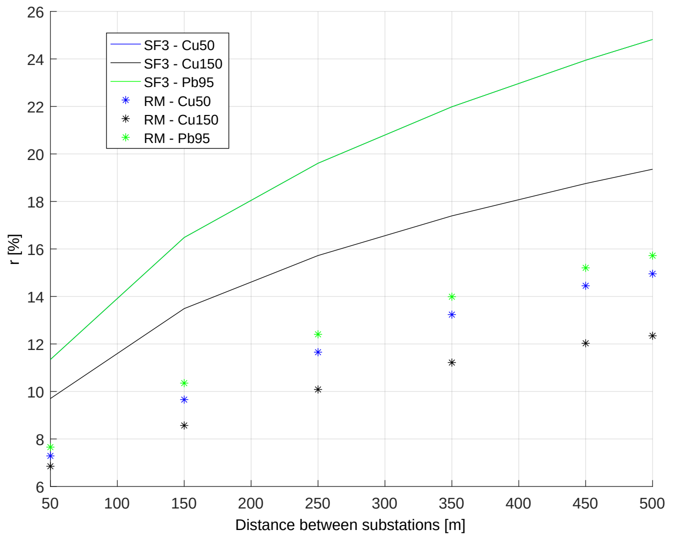

Figure 1. Comparison between the reduction factor computed by RM and by the simplified formula 3 for different MV cables.

It is important to underline that the coefficients used in the fittings shown in Fig. 1 were selected in order to keep computed r values always higher than the ones adopted as reference to the sake of safety.

B. Position of the MV/LV substation affected by the fault with reference to the HV/MV substation

The position of the substation affected by the fault in the MV feeder has a great influence on the fault current distribution.

To model this phenomenon, a multiplying coefficient for the reduction factor r was designed:

$$\left.\frac{r}{r_{Ref}}\right|_{F_L} = \frac{1}{F_L} \tag{4}$$

where F_L is the fault location coefficient reported in Table III. These values derive from the parametric analysis reported in [5], where it was shown that if MV cable sheaths are disconnected from the earthing systems of the HV/MV substations, a fault in the first MV/LV substation of the feeder represent the worst case . According to this, for the sake of safety, the coefficient F_L in SF (1) is set to 0.8 for each of the first five MV/LV substations in a feeder. For the other substations, F_L is 1.5, as the ratio between the SLGF current caused by a fault in the first and in the last substation.

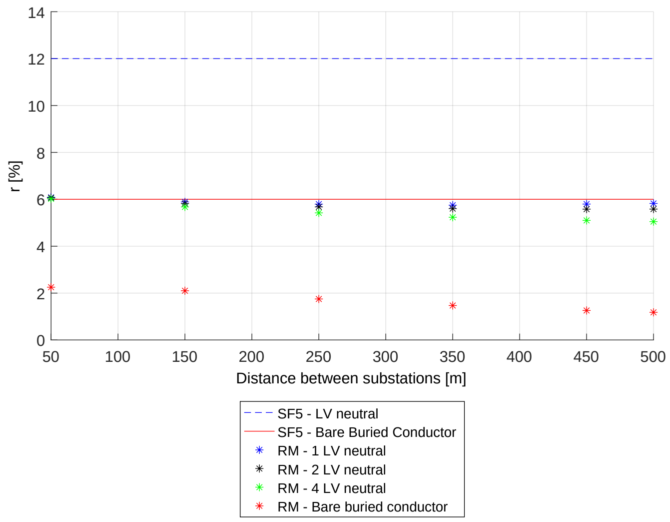

Figure 2. Comparison between the reduction factor computed by RM and by the simplified formula 5 with changes in the interconnection level.

C. Additional interconnections among ESs due to LV neutral conductors, bare buried conductors or MV cable shields

In high density urban areas, the earthing network could be more meshed thanks to the LV neutrals or additional MV cables; moreover, some DSOs use to bury a bare conductor, which is connected in parallel with the MV cable shield.

In order to consider these additional interconnections, eq. (3) was modified as in eq. (5):

$$r = \frac{3}{k_{i1}} \cdot L^{k_{i2} \cdot c} \tag{5}$$

As shown in [5], extra interconnections reduce the importance of the distance between substations. According to this, k_{i2} is set equal to 0 every time that this scenario occurs.

In order to keep simple the expression of r, the number of the extra interconnections was not taken into account. Moreover, in first approximation, interconnections made by MV cable shields or by LV neutral conductors were considered equivalent.

By fitting the r values computed by RM, it was possible to identify the numerical values of the coefficient k_{i1}, reported in Table II.

The comparison between the reference values and those computed by the simplified eq. (5) is presented in Fig. 2.

D. Earth resistance of the faulted substation with respect to the neighboring ones

Another parameter that influences the fault current distribution is the ratio between the resistance to earth of the faulted substation, R_E, and the resistance to earth of the neighboring ones [5].

To model this phenomenon, a multiplying coefficient for the reduction factor r was designed (6):

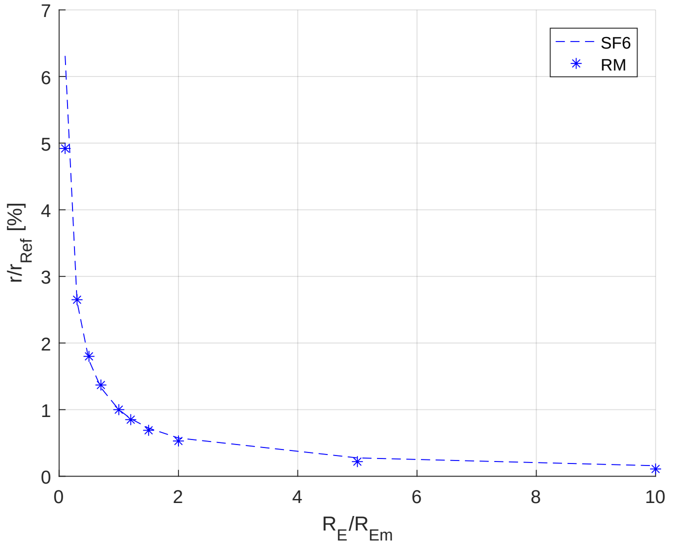

Figure 3. Comparison between the normalized reduction factor computed by complete model and by the simplified formula 6, with changes in the resistance to earth of the faulted substation with respect to the neighboring ones.

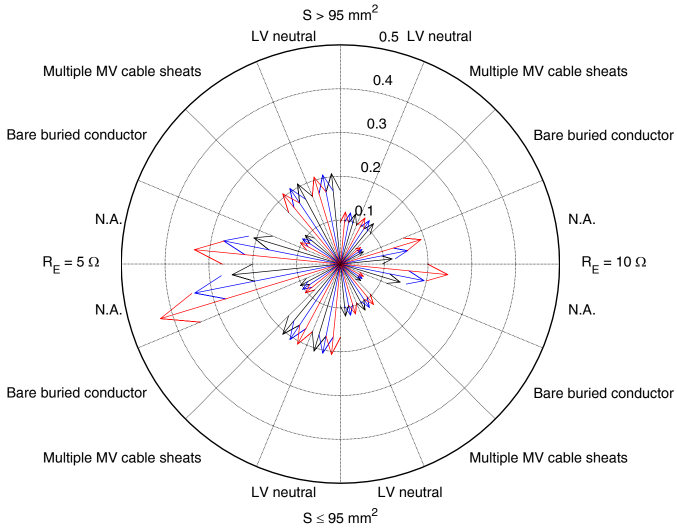

Figure 4. Parametric analysis: Reduction factor for the first 5 substations with reference to the HV/MV station. The arrow length is the value of r and its color indicates the length of the cable connecting two consecutive substations (black = 100 m; blue = 250 m; red = 500 m). Each slice represents a different combination of R_E and the interconnection level (table II).

$$\frac{r}{r_{Ref}}\bigg|_{R_E/R_{Em}} = \left(\frac{R_E}{R_{Em}}\right)^{-0.8} \tag{6}$$

where R_{Em} is the average resistance to earth, computed as the mean value of the N substations in the set S_i.

The comparison between the reference values and those computed by the simplified eq. (6) is presented in Fig. 3.

E. Number of the interconnected MV/LV substations

According to [5], the number of interconnected MV/LV substations N has a great impact on the reduction factor just until $N < 10$. In order to keep simple the computation of r, this factor of influence was not explicitly considered in the proposed model. However, for the sake of safety, it was specified as a working hypothesis: to use eq. (1), it shall be verified that $N \geq 10$.

IV. Parametric Analysis

In order to investigate the values assumed by the reduction factor r computed by SF (1), a parametric analysis was carried out. SF (1) was applied to two hypothetical substations: the first one belonging to the first 5 MV/LV substations (with reference to the HV/MV station); the second not. For each of them, 16 different scenarios were considered.

In Fig. 4, drawn considering the substation closest to the HV/MV station, each arrow stands for a scenario: the arrow length is the value of r, its color indicates the length of the cable connecting two consecutive substations (black = 100 m; blue = 250 m; red = 500 m), while its position shows the other input parameters that characterize each scenario. Always considering $R_{E_m} = 7.5\ \Omega$, on the first and fourth quadrants there are the cases with $R_E = 10\ \Omega$, while on the second and third ones those where $R_E = 5\ \Omega$. Analogously, the cases with

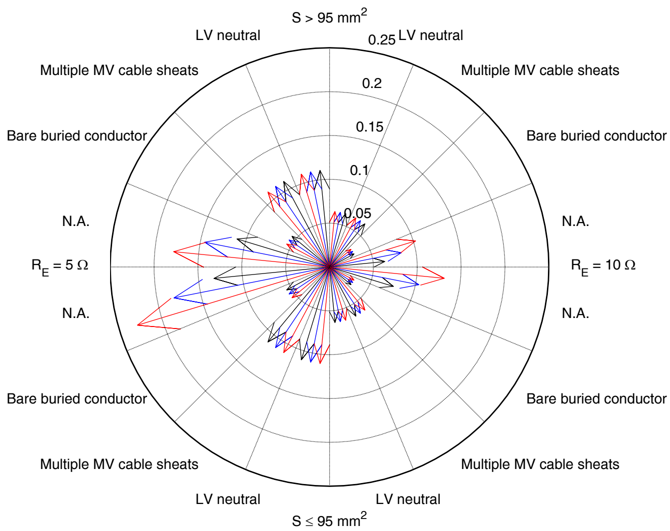

Figure 5. Reduction factor for the substations that are further away from the HV/MV station (starting from the 6th). The arrow length is the value of r and its color indicates the length of the cable connecting two consecutive substations (black = 100 m; blue = 250 m; red = 500 m). Each slice represents a different combination of R_E and the interconnection level (table II).

$S > 95\ mm^2$ lay on the first and second quadrants and those with $S \leq 95\ mm^2$ are on the remaining ones. Lastly, each sector stands for one of the interconnection level of table II. In the same manner, graphs in Fig. 5 represent the reduction factors r valid for the substation far away from the HV/MV station (starting from the 6th substation).

The order of magnitude of r computed by eq. (1) can be compared with those measured in [13], [18], [19], and a good agreement can be noticed. Once again, just a little percentage of the fault current flow through the ES of the faulted

Table V
Characteristics of the MV test branch.

Characteristics		Value/State
Rated voltage	[kV]	22
SLGF current	[A]	284
Neutral	-	isolated from ground
Cable section	$[mm^2]$	185
Phase resistance	$[\Omega/km]$	0.164
Sheat resistance	$[\Omega/km]$	0.730
Phase-sheat capacitance	$[\mu F/km]$	0.300

substation. Viceversa, a great difference can be observed with reference to the range suggested by EN 50522 in Annex I ($20\% \leq r \leq 60\%$) [2].

V. Case study

The SF 1 was applied to the feeder of a real urban network (Fig. 6), already chosen as test case in [20].

The main characteristics of the feeder (such as the rated voltage, the SLGF current, the properties of the adopted MV cable) are reported in Table V.

An insulating joint separates the MV cable sheaths from the earthing system of the HV/MV station.

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.

The ES of each MV/LV substation is formed by a grounding ring buried at 0.75 m from the soil surface. The local Resistances to Earth (R_Es) are not available and therefore a typical value of 5 Ω was considered for all the ESs.

For the considered network, knowing the SLGF current (computed by DSO) and the R_E of each earthing systems, it is possible to compute the EPR for each of the MV/LV substations through eq. (7):

$$EPR = r \cdot I_{SLGF} \tag{7}$$

In Fig. 7, the comparison between the maximum EPR computed by both RM and eq. (7) with *r* obtained by the simplified formula (1) is reported for all the MV/LV substations. In order to better quantify the risk level, U_{Tp} is also evaluated, according to Table B.3 of EN 50522.

As desired, SF (1) provides values of the reduction factor always greater than RM. The safety margin, computed as percentage difference, is in the range $33 \div 230[\%]$.

A similar trend can be noticed between the EPR curves in Fig. 7. When additional interconnections among ESs are present (such as in substation 14, 23 and 24), the reduction factors calculated by both the RM and SF decrease. A significant difference can be noticed in substation 6, due to the length of the cables adopted. This difference is highlighted because substation 6 is the last one for which coefficient FL is set equals to 0.8.

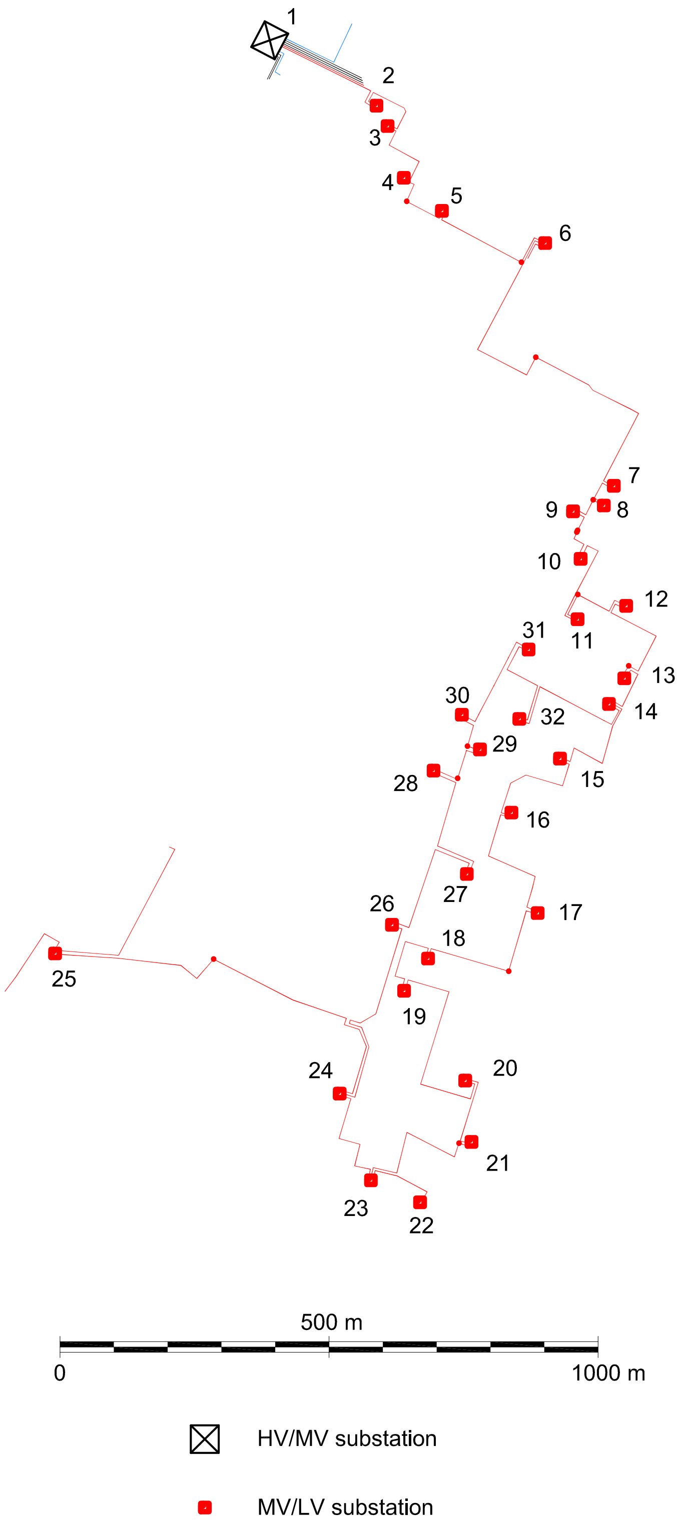

Figure 6. MV feeder considered for the case study.

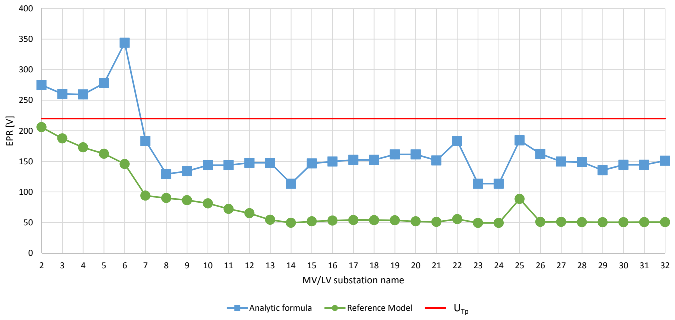

Figure 7. Comparison between the permissible touch voltages and the maximum EPRs computed by both RM and SF (1).

VI. Conclusion

The identification and the certification of a Global Earthing System (GES) could provide great benefits for both DSOs and MV Users, as the design and verification procedures of MV/LV substations earthing systems that belong to a GES are significantly simplified. Unfortunately, this objective is not easy to fulfill, because no standard procedure has been defined. The main factor that characterizes a GES is the fault current distribution among the interconnected ESs and a first step towards the identification of GESs would be the possibility to easily and reliably evaluate the reduction factor in each substation.

In this work, a formula to compute the reduction factor, based on the results of a parametric analysis, is presented, as well as its rationale. To use it, two conditions shall be verified: first, the MV neutral point shall be isolated from ground; second, the feeder shall be formed by at least 10 MV/LV substations.

The formula takes into account the properties of the MV cables, the position of the MV/LV substation with reference to the HV/MV/substation, additional interconnections among ESs (such as LV neutrals or bare buried conductors), the earth resistance of the MV/LV substation with respect to the neighboring ones.

The formula was applied as a test to a real MV urban feeder and, even if several factors are considered, it is simple to use and provides results that not significantly differ (except for the desired safety margins) from those obtained by a much more complex model, which vice versa could be quite complicated to use.

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