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(Article begins on next page)

04 August 2020

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Abstract – **Global Earthing Systems (GES), created by the interconnection of local earthing systems, should guarantee the absence of dangerous touch voltages. One of the reasons for this safety characteristic of GES is the fault current distribution between grounding electrodes and MV cables sheaths: only a small portion of the fault current is injected into the ground by the ground-grid of the faulty substation. In systems with isolated neutral or with resonant earthing this effect may be sufficient to provide safety from electric shock.**

In this paper a model describing the behavior of the MV distribution system with interconnected grounding electrodes during a ground fault is built. It is then used to analyze the impact of different factors on the fault current distribution. A sensitivity analysis is performed varying the main parameters and the results are used to draw some conclusions on the current distribution influence on global earthing systems.

Index Terms -- **Electrical safety, Global earthing systems, Grounding, Power distribution faults, Single line to ground fault.**

I. ACRONYMS

DSO   Distribution System Operator
EPR   Earth Potential Rise
GES   Global Earthing System
HV   High Voltage
LV   Low Voltage
MV   Medium Voltage
SLGF   Single Line to Ground Fault

II. INTRODUCTION

The CENELEC Harmonization Document HD 637 S1, published in 1999 [1], and, later, the European EN 50522 [2] and International IEC EN 61936-1 [3], [4] Standards (published in 2010-2011) introduced, with reference to MV distribution systems, the concept of global earthing system (GES), that is defined as "equivalent earthing system created by the interconnection of local earthing systems that ensures, by the proximity of the earthing systems, that there are no dangerous touch voltages". Typical examples of global earthing systems could be found in city centers, because of the high density of interconnected MV/LV substations [5]. Experimental measurements have shown in fact that in interconnected MV distribution systems the cases where the permissible earth potential rise (EPR) was exceeded concerned only stand-alone substations (in antenna or situated at long distance from other substations) [6].

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. Normally, in fact, the ground-grid is designed to respect the total EPR or the touch and step voltages, based on the prospective single-line-to-ground-fault (SLGF) current magnitude and time required to clear the ground-fault itself (data communicated by the DSO). In addition to this, the safety assessment should be carried out on a regular basis, to detect modifications in the ground-grid performances or evaluate the impact of SLGF current level increase [7]. In presence of a GES, instead, the safety of the system with respect to touch and step voltages is intrinsically assured [2],[3],[4], and so both design and verification procedures would be simplified. Up to now however no simple or stand-alone rules or procedures are actually available in order to identify GES areas [5], [8].

MV distribution systems in urban areas generally consist of a large number of MV/LV substations close to each other. Each substation is provided with grounding electrodes characterized by a quite high resistance value. All grounding systems are interconnected through cable sheaths and, sometimes, through bare ground wires buried together with power cables or through LV neutral conductors. This close interconnection of the grounding systems to each other and to utility installations (water/gas pipelines, railway tracks, etc.) sets up an overall low resistance grounding system and has mainly two effects:

- a distribution of the fault current between grounding electrodes (of the faulty substation and of the neighboring ones) and MV cables sheaths [9],[10],[11];
- a smoothing of the earth surface potential profile, reducing the hazardous voltage gradients [12],[13].

In general many factors need to be considered for the assessment of the safety of such interconnected grounding system prior to its classification as GES:

- a low grounding resistance is helpful, but is not a guarantee. Therefore, the identification of a GES cannot be based only on the grid resistance value;

- a low fault current level is helpful as the EPR will be limited;
- a low reduction factor, related to earth wires of overhead lines and metal sheaths of underground cables, distributes the fault current in such a way that the EPR is limited;
- a short fault duration increases the permissible touch voltages.

In this paper particular attention is given to the fault current distribution between grounding systems and cable sheaths in a MV distribution system with interconnected grounding electrodes. A model, describing the behavior of the system during a ground fault, is used to analyze the impact of different factors on the fault current distribution [13],[14].

The main factors influencing the fault current distribution are [10]:
- the number of MV/LV interconnected substations in the area;
- the distance between MV/LV substations;
- the technical characteristics of the MV power cables;
- the number of LV lines powered by each MV/LV substation (i.e. the number of substations connected through LV neutral conductors);
- the presence of bare buried conductors connecting the substations;
- the position of the substation affected by the fault in the MV line;
- the connection of the MV cables sheaths to the ground-grid of the HV/MV Substation;
- the ground-grid earth resistance of the faulted substation and of the neighboring ones.

In the following paragraphs the structure of the considered MV distribution systems is described, the model used for the simulations is presented and a sensitivity analysis is carried out varying the previously described parameters. Finally the results are used to draw some conclusions on the presence of a possible global earthing system.

III. STRUCTURE OF MV DISTRIBUTION SYSTEMS

MV distribution systems are designed to carry electrical power from the transmission system to individual consumers. They are fed by HV/MV transformers located in distribution substations and feed LV users through MV/LV distribution transformers. Mainly because of historical reasons and population density, in Europe and in North America they are quite different in structure.

In North America residential loads are fed by single phase MV/LV transformers and MV lines are thus equipped with a neutral conductor to ensure the return of the unbalance load current. All the grounds along the line, including those of customers, are connected to the neutral conductor and constitute an extended grounding system called "multigrounded neutral" [15],[16],[17].

In Europe instead all LV users are fed by three phases transformers located in MV/LV substations. Most MV lines are constituted, especially in urban areas, by buried cables. The neutral point of the MV distribution systems is isolated from ground or earthed through the so called "Petersen coil" for SLGF current reduction (resonant earthing). For these reasons the fault can last for a certain time before being cleared [18].

In this paper the typical Italian MV distribution systems are described and analyzed, in particular for what concerns the ground-grids interconnection.

Usually a single HV/MV substation feeds a few MV lines, which, on their path, feed 10 to 20 MV/LV substations each. Every MV line can be fed from both ends but 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.

The cables metal sheaths are earthed at each end, being connected to the ground-grid of each substation. The only exception can be at the HV/MV substation, where sometimes, to limit the problem of exported dangerous voltages in case of SLGF on the HV side, an insulating joint is placed and the MV cable sheaths are not connected to the ground-grid.

The described situation sets up an overall interconnected grid of grounding electrodes, which is even more meshed, thanks to LV neutral conductors. LV consumers, in fact, can be fed (not at the same time) by two different MV/LV substations in order to improve the system reliability. As in the case of MV cables, also LV phases are disconnected in a distribution box along their path to make the LV network radial, but LV neutrals are never disconnected, creating a connection between ground-grids of different MV/LV substations, even belonging to different MV lines.

Certain DSOs, when installing new MV lines, are used to bury in the excavation a bare conductor together with the power cables. This bare conductor constitutes a further interconnection between the ground-grids of the substations, also contributing to the current injection into the ground [19],[20],[21].

The overall situation is described in Fig. 1, where MV lines (continuous), cables sheaths (dash-point) and LV neutral conductors (broken-line) are highlighted.

In case of SLGF, in general the fault current I_F can be calculated as:

$$I_F = 3\,I_0 + I_N \qquad (1)$$

where I_0 is the zero sequence current of the line and I_N is the current via the neutral earthing of the transformer [2]; in systems with isolated neutral, $I_N = 0$. Thanks to the previously described interconnections, in the faulted substation the current I_F is distributed between the ground-grid (I_{RS}), the MV cables sheaths (I_S), the LV neutral conductors (I_{LVN}) and the bare buried conductors (I_{BC}), if present (Fig. 2).
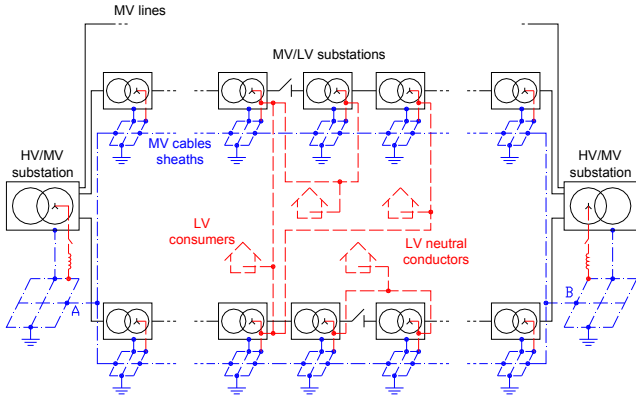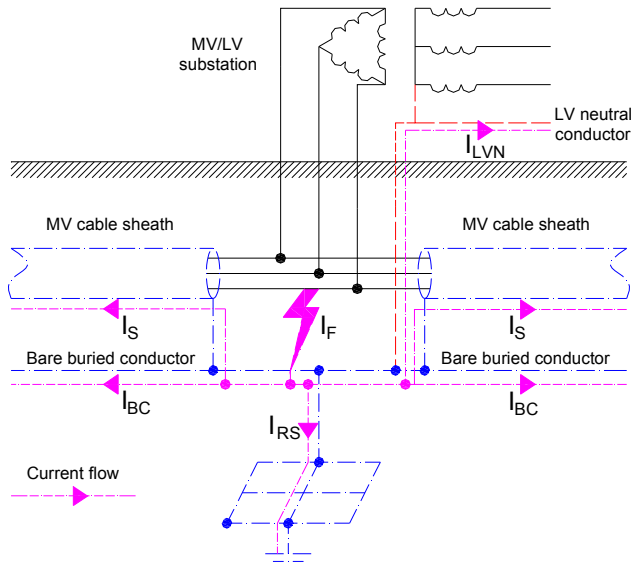
Fig. 1. MV distribution system.

Fig. 2. SLGF current distribution.

The Italian MV distribution systems were historically designed and built in order to operate with their neutral point isolated from ground; in recent years, however, Petersen coils are being installed in a growing percentage of the HV/MV substations. However, also in the distribution systems where the Petersen coil is in operation, the SLGF current is not completely compensated but its magnitude is only reduced to around 50 A to enable a reliable fault localization and line tripping.

IV. SIMULATION MODEL

For the simulation of a SLGF analytical models of the components of a generic MV distribution system have been developed [10],[14],[19],[20],[21]. The blocks representing the different components can be assembled to represent the desired MV distribution system. Finally the full model is solved using the node method to calculate the currents in all branches and the voltages in all nodes [22]. To optimize the calculation time and to reduce the rounding errors, the system of equations is solved using the Gaussian elimination method

with partial pivoting [23]. In the following paragraphs the models of the main system elements are described. In Fig. 3 an example of simulation model for a very simple case is presented and the different blocks are highlighted.

A. HV/MV Substation

The block that represents the HV/MV substation contains the model of the secondary windings of the HV/MV transformer (ideal voltage source and series impedance - E1, E2, E3 and z in Fig. 3), the model of the HV/MV substation ground-grid (Rehv in Fig. 3) and the model of the portion of distribution network that is not explicitly represented (Radd and Cl in Fig. 3). The magnitude of the SLGF current depends in fact on the network size (i.e. kilometers of MV lines fed by the same HV/MV transformer). Representing in the model all the MV lines fed by the HV/MV transformer would however result in a huge increase in the computation time and problem complexity. For this reason only the interesting portion of the system for the currents distribution evaluation is represented explicitly, while the rest of the system is modeled through equivalent impedances.

B. MV/LV Substations

The block that represents the MV/LV substation contains the resistance that models the ground-grid (Re in Fig. 3).

C. MV lines and LV neutral conductors

All substations in a MV line are interconnected through MV cables, which can be single-core or three-cores. In some cases, as previously described, a bare conductor can be buried together with the MV cables. This originates 4 different MV connection typologies, which are modeled by 4 different blocks. In all 4 cases, the impedance of each conductor (3 phases, cable sheaths, ground, bare buried conductor) is considered, together with its capacitive and inductive coupling with all other conductors (in Fig. 3 u, v, w are the phase conductors, s is the cable sheath, bc is the bare buried conductor). Ground is modeled according to Carson's theory (conductor g in Fig. 3). If a bare buried conductor is present, its ground conductance (gbc in Fig. 3) is considered [19],[20].
In order to simulate also the interconnection of ground-grids of MV/LV substations of different MV lines, also LV neutral conductors are modelled, through the impedance of the conductor itself (lvn in Fig. 3), coupled with ground return.

D. Ground fault

The SLGF is modelled by a low impedance connection between one phase and the ground-grid of the faulted substation (substation B in Fig. 3).
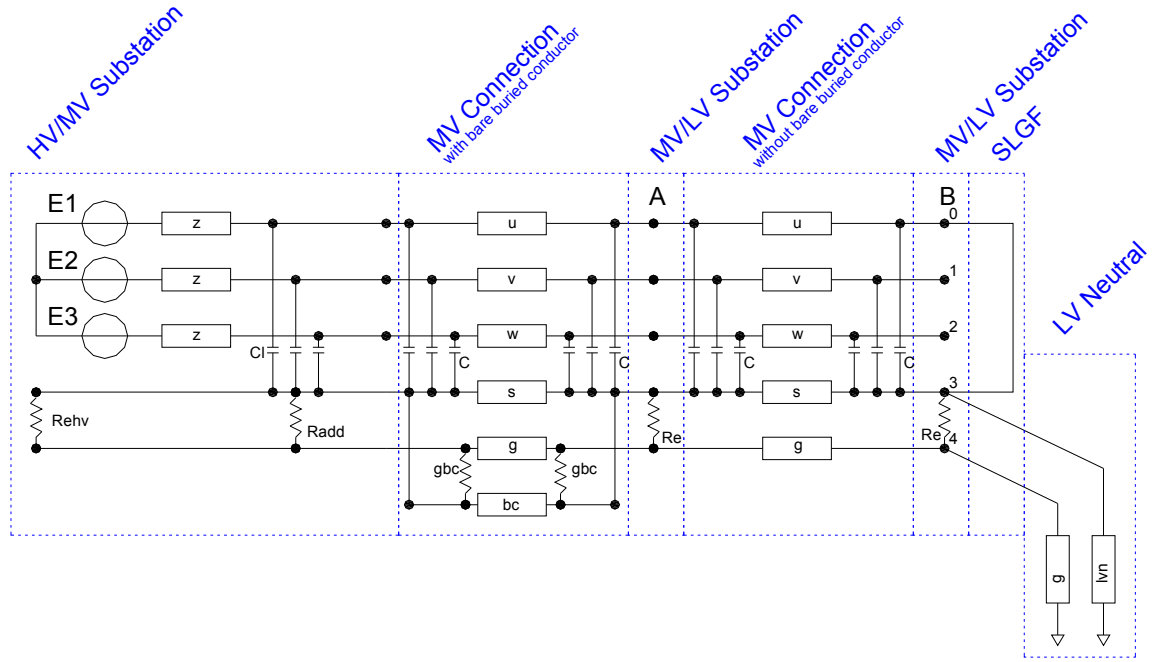
Fig. 3. Simulation model

V. SENSITIVITY ANALYSIS AND RESULTS

The analytical model described in the previous section is applied to different test cases, varying the main parameters, in order to analyze the impact on the fault current distribution and its implications for the GES definition.

To judge the effectiveness of the interconnection from the point of view of the current distribution between cable sheaths, bare buried conductors and substation ground-grid the ratio R_{eq}/R_e is used [13], where R_{eq} is the equivalent resistance seen by the fault current at the faulted substation and R_e is the earth resistance of the same substation. R_{eq} can be calculated with equation (2):

$$R_{eq} = U_e / I_F \qquad (2)$$

where U_e is the EPR of the faulted substation. The ratio R_{eq}/R_e is equivalent to the ratio I_{RS}/I_F used by other authors [10], where I_{RS} is the portion of the SLGF current injected into the ground in the faulted substation (Fig. 2), as shows equation (3).

$$\frac{R_{eq}}{R_e} = \frac{\dfrac{U_e}{I_F}}{R_e} = \frac{R_e \cdot I_e}{R_e \cdot I_F} = \frac{I_{RS}}{I_F} = \frac{U_e}{U_{e0}} \qquad (3)$$

The ratio R_{eq}/R_e is also equivalent to the ratio U_e/U_{e0} – eq. (3) – where U_{e0} is the EPR in the faulted substation when all the fault current is injected into the ground (substation disconnected from the neighboring ones).

The chosen ratio is therefore a measure of the advantages achieved thanks to the interconnection of the substation ground-grids from the point of view of the equivalent resistance reduction, of the fault current distribution and of the EPR reduction.

For the sensitivity analysis two distribution network layouts were considered, not matching any real one, but inspired by the distribution network in Torino, Italy. In the first layout (Fig. 4) the explicitly represented portion of network is made of 16 MV/LV substations interconnected by an "S" shaped MV line.

In the second layout (Fig. 5) the explicitly represented portion of network is made of 64 MV/LV substations, on four parallel MV lines (16 substations each).
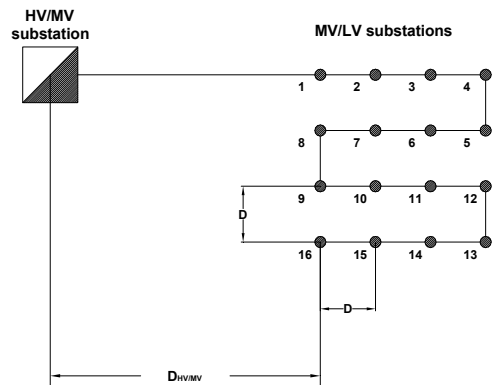

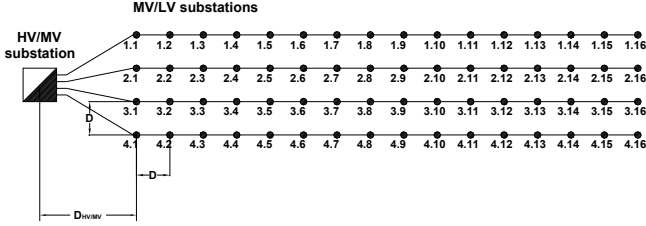Fig. 4. First distribution network layout (S-layout)

Fig. 5. Second distribution network layout (parallel-layout)

The first layout is useful to analyze the case in which LV neutral conductors interconnect different substation of the same MV line, while the second case is useful to analyze the case in which LV neutral conductors interconnect substations belonging to different MV lines. Both layouts are obviously simplified: in real cases the geometry of distribution networks is more complex. They are however useful for the intended analysis. In both studied layouts there is a non-represented portion of the network, fed by the same HV/MV transformer, modelled in the HV/MV substation block in order to obtain the desired SLGF current magnitude. The simulations have been carried out on both layouts but here, for the sake of brevity, as the results are similar, only the S-layout results are reported.

In Table 1 the characteristics of the studied systems and in Table 2 the cable types used for the simulations are summarized. The neutral point of the distribution system is isolated form ground.

TABLE 1
SYSTEM CHARACTERISTICS

Network rated voltage	22 kV
Earth resistivity	100 Ωm
Earth resistance of the HV/MV substation	1 Ω
Earth resistance of the MV/LV substations	10 Ω
Apparent power of the HV/MV transformer	63 MVA
Short circuit voltage of the HV/MV transformer	13 %
Non-explicitly simulated MV lines Cl (S-Layout)	5.5 µF
Non-explicitly simulated MV lines Radd (S-layout)	6.4 S
Non-explicitly simulated MV lines Cl (parallel-layout)	1.4 µF
Non-explicitly simulated MV lines Radd (parallel-layout)	1.6 S

TABLE 2
MV CABLES

MV Cable	A	B	C	D
Phase conductor cross section [mm^2]	50	150	240	95
Phase conductor resistance [Ω/km]	0.441	0.144	0.09	0.222
Sheath material	Cu	Cu	Cu	Pb
Sheath mean diameter [mm]	20	26	30	18
Sheath resistance [Ω/km]	1.15	0.73	0.73	1.8
Capacitance between phase conductor and metal sheath [µF/km]	0.204	0.348	0.423	0.297

In the following paragraphs the different sensitivity analysis results are presented.

A. *LV neutral conductors*

For the first analysis (Fig. 6), cable B has been used,

varying the distance D between the substations and the number of LV neutral conductors (cross section of 50 mm^2) connected to each substation (that is associated to the number of LV lines fed by the substation). The effect of the interconnection through LV neutral conductors is compared to that produced by bare buried conductors (cross section 95 mm^2).
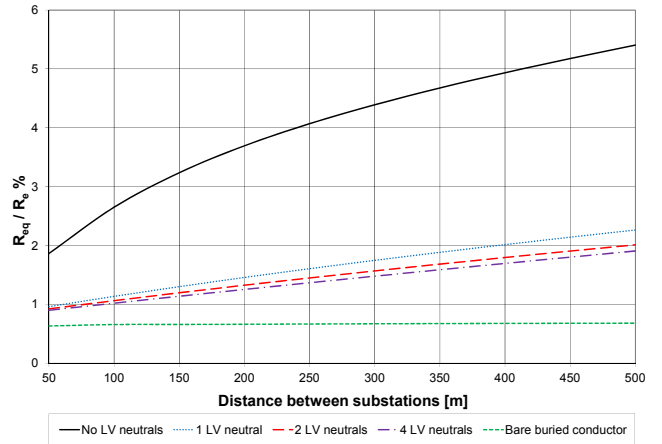

Fig. 6. Effect of LV neutrals and bare buried conductors

The results show that even when the MV/LV substations are interconnected only through the cables sheaths, the percentage of fault current injected into the ground is only some percent of the total fault current. When LV neutral conductors interconnect the substations the ratio is greatly reduced, but also its dependency from the distance between substations is reduced. When a bare conductor is laid in the ground together with MV cables the ratio is reduced even more and the distance between substations ceases its effect.

B. *Characteristics of the MV power cables*

In Fig. 7 the effects of the MV power cables are analyzed, varying the distance D between the substations without LV neutral conductors.
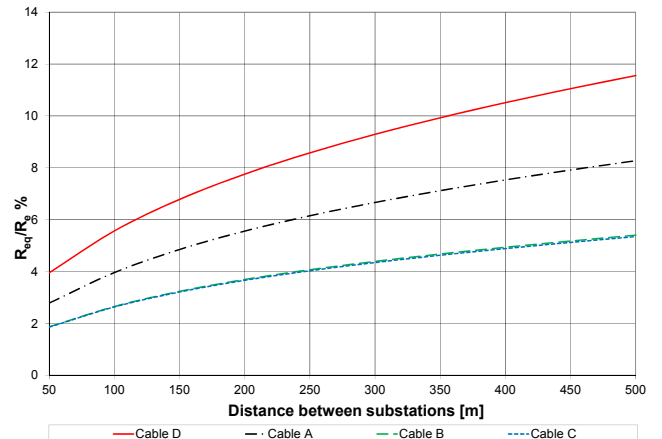

Fig. 7. Effect of MV cable characteristics

Only the sheath cross section and material are important parameters for the R_{eq}/R_e ratio reduction: in fact the two cables (cable B and cable C) with different characteristics but with the same sheath resistance have the same performance.

C. *LV neutral conductors and MV power cables*

In Fig. 8 the combined effects of LV neutral conductors and MV cable characteristics are presented. The best and worst cable of Fig. 7 are used, with 1 or 4 LV neutral connections per substation.
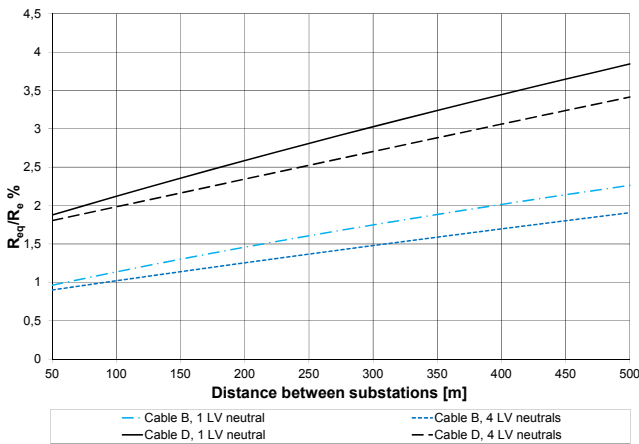

Fig. 8. Effect of LV neutrals and MV cable characteristics

D. *Fault location and connection to the HV/MV substation*

Two important factors influence the SLGF current distribution: the position of the substation affected by the fault in the MV line and the connection of the MV cables sheaths to the ground-grid of the HV/MV substation which feeds the MV line. In order to analyze these aspects, the simulations have been carried out (cable B, distance between substations 250 m) with the MV cables sheaths connected/disconnected from the HV/MV substation ground-grid and locating the fault in substation 1, 7 or 16 (Fig. 4). The results are presented in Fig. 9 and Fig. 10 for connected/disconnected HV/MV substation respectively.
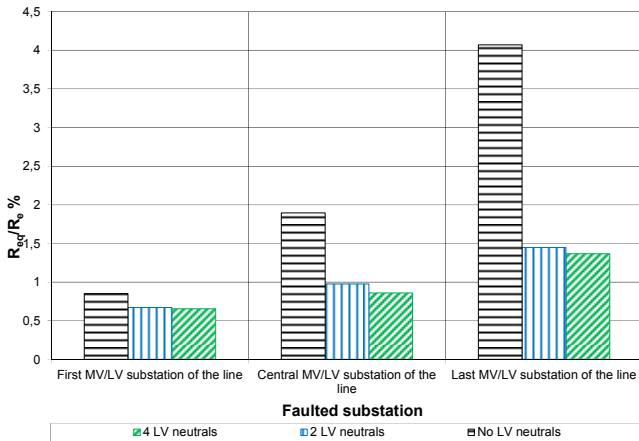

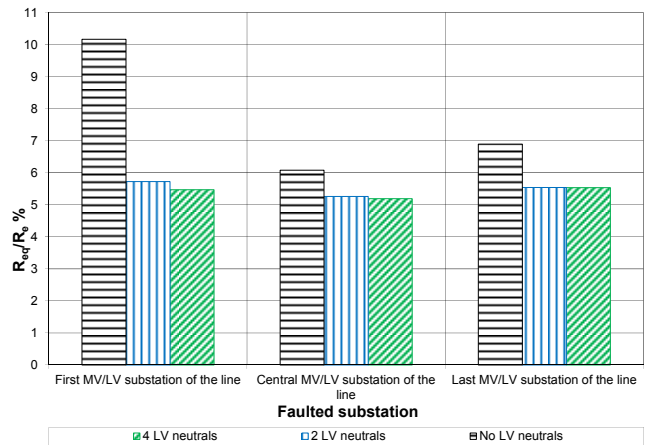Fig. 9. Effect of the fault location – connected HV/MV substation

Fig. 10. Effect of the fault location – disconnected HV/MV substation

For the SLGF on the MV system, the connection of cables sheaths to the HV/MV substation ground-grid is greatly beneficial, as it globally lowers the R_{eq}/R_e ratio. In fact, not only in this case the ground-grid of the HV/MV substation is involved in the fault current injection into the ground, but also a portion of the fault current can reach the other MV lines without flowing through the ground.

Fig. 9 and Fig. 10 show also that one of the effects of the interconnection through LV neutral conductors is to make the fault current distribution nearly independent of the fault location.

E. *Number of interconnected MV/LV substations*

The number of MV/LV interconnected substations in the area is one of the main factors that needs to be taken into account. In Fig. 11 the number of MV/LV substations fed by the MV line (S-layout) is varied from 1 to 16.
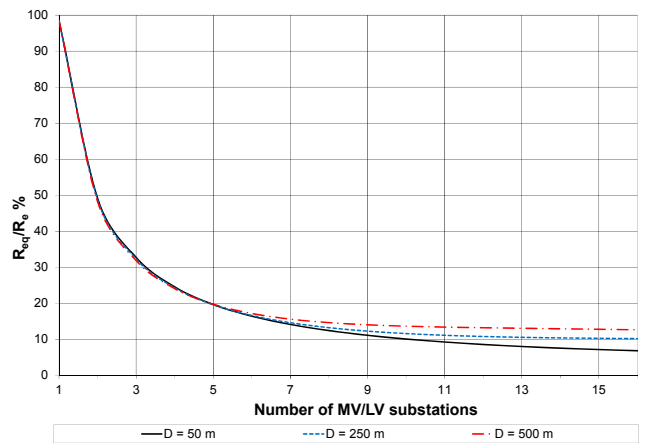

Fig. 11. Effect of the number of interconnected MV/LV substations

The fault is always located in the first substation of the line and the cable sheaths are disconnected from the HV/MV substation, as these were recognized as the worst conditions (see previous paragraph). The simulations are carried out using cable B and for distances between substations of 50 m,

25 m and 500 m.

The results show that for normal distances between substations (i.e. 250 – 500 m), above a number of 10 interconnected substations the ratio R_{eq}/R_e is not decreasing any more.

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

Another important factor that influences the current distribution and therefore the EPR in the faulted substation is its ground-grid earth resistance with respect to the neighboring ones. In all the previously presented simulations all the MV/LV substations were supposed to have the same earth resistance, $R_e = 10$ Ω. Here all substations maintain the same value of earth resistance, only the earth resistance of the faulted one is varied from 1 Ω to 1k Ω.

In Fig. 12 the ratio R_{eq}/R_e and the EPR are reported. It appears that when R_e is increased, the current injected into the ground in the faulted substation decreases with a lower gradient: the EPR is therefore increasing.
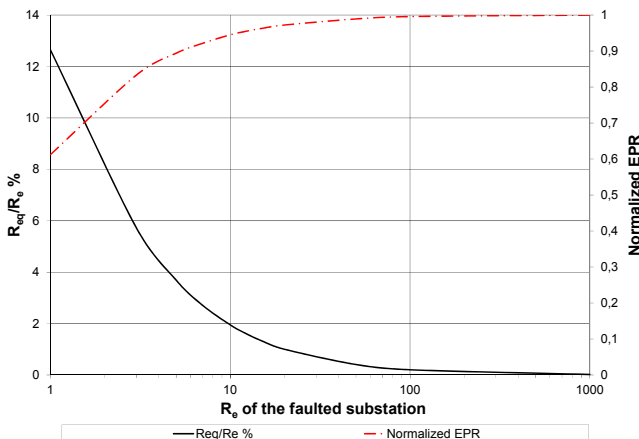

Fig. 12. Effect of the earth resistance of the faulted substation

G. Comparison and final comments on the results

The results presented here can be compared with the measurements performed by Fickert et al. [24], even if they were not performed on a real SLGF due to the earthing of one of the healthy phases through a resistance in the HV/MV substation. In [24] the ratio I_{RS}/I_F was found to be in the range 3% - 4%, and a big portion of the fault current was measured on MV cable sheaths and LV neutral conductors, in agreement with the results presented here (Fig. 6, Fig. 7, Fig. 8).

Desmedt et al. [6] propose that a GES should be constituted by at least 20 interconnected MV/LV substations, provided that their mutual distance D is not greater than L, where:

$$L = 500 \frac{S_m}{16} \qquad (4)$$

and S_m is the weighted average cross-section of the protective conductors forming part of the connection, in mm^2.

In alternative, according to [6], a GES is assumed to exist if the system involves a set of cables with earthing effect (i.e. with bare buried conductors) of at least 1 km and if the mean length of each part of cable without earthing effect doesn't exceed L. This alternative requirement is in perfect agreement with the results presented here. The presence of bare buried conductors, in fact, reduces the current I_{RS} to less than 1% of the total I_F and makes the substations mutual distance irrelevant.

The second requirement ($D \leq L$) instead keeps into account the right parameters, the distance D and the sheath cross section, but does not consider different materials (many cables still have a Pb sheath): the correct parameter to be considered should be the per unit length resistance of the cables sheaths.

An important element that is not considered in [6] is the presence of LV neutral conductors, which makes the substations mutual distance less important.

VI. CONCLUSION

In this paper, a model describing the behavior of a MV distribution system with interconnected grounding electrodes during a SLGF is built and applied to two simplified layouts.

With respect to the two main effects of the interconnection – a distribution of the fault current between grounding electrodes and MV cables sheaths and a smoothing of the earth surface potential profile – the authors believe that the first one is the principal responsible for GES safety. The simulation model is therefore used to analyze the impact of different factors on the fault current distribution.

The main factors which influence the fault current distribution (and therefore the equivalent resistance reduction) 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. These are the factors that should be taken into account for the GES definition.

The MV cables characteristics (except for the per unit length resistance of the sheath) vice versa seem to be irrelevant for the fault current distribution.

The habit of certain DSOs of burying in the excavation a bare conductor, together with the power cables when installing new MV lines, is one of the best solutions for lowering the equivalent resistance and reducing the portion of the fault current injected into the ground in the faulted substation. This bare conductor, in order not to constitute only a further interconnection between the ground-grids of the substations, but also to contribute to the current injection into the ground, should be directly placed in the excavation and not inside the protective pipe used for the MV cables.

The main factors presented in this paper, together with the fault clearing time and the SLGF current magnitude of the considered distribution system should be used for the

definition, identification and official classification of Global Earthing System.

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