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Safety performance evaluation of typical grounding configurations of MV/LV distribution substations

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ABSTRACT

Typical grounding configurations are used in MV/LV distribution substations often without evaluating their safety performance against the danger of critical electric shock due to touch and step voltages arising in case of a ground fault. A method for the straightforward safety assessment of typical grounding configurations of MV/LV substations is introduced on the basis of simple calculations. A safety performance curve is constructed by using proportionality factors, specific to each typical grounding configuration, and the time–current characteristic of the installed protective device. The safety performance curve relates ground fault current to upper limits of soil resistivity, thus also ground resistance, below which safety is ensured. Thus, safety of an existing or new MV/LV substation can be easily evaluated through the associated safety performance curve. In a similar approach, a method is introduced to determine the shortest separation distance between MV/LV substation and LV neutral grounding configurations ensuring safety against transferred potentials where common grounding is not applied. The use of the proposed methods is demonstrated through an application to typical 20/0.4 kV distribution substations.

1. Introduction

The grounding system of a technical installation should allow for the flow of steady-state or fault currents to the ground without exceeding equipment and operating limits or affecting the continuity of service [1]. In addition, and most important, it should afford protection to persons against the danger of critical electric shock [1]; this has been investigated in several recent studies [2–6]. The safety performance of the grounding system of high voltage installations should always be evaluated for the most dangerous ground fault. However, typical grounding configurations are utilized in MV/LV distribution substations often without evaluating their safety performance. This may expose utility personnel as well as the general public to the danger of critical electric shock due to touch and step voltages arising in case of a ground fault.

In addition, where common grounding between MV/LV substation and LV neutral grounding configurations is not applied, a fixed distance between the separate grounding configurations is utilized most commonly without safety assessment; this may endanger persons and LV equipment due to potentials transferred through the LV system neutral owing to ground faults occurring at the MV side of the substation.

In the present study a method for the straightforward safety assessment of typical grounding configurations of MV/LV distribution substations is introduced. The method is based on simple grounding analysis calculations employing proportionality factors specific to the evaluated grounding configuration. Using also the time–current characteristic of the installed protective device, a safety performance curve is constructed. This curve relates ground fault current to upper limits of soil resistivity, thus also ground resistance, below which safety is ensured, that is, the allowable touch and step voltages are not exceeded. The safety performance curve allows for the direct safety assessment of an existing or new MV/LV substation typical grounding configuration.

In a similar approach, a method is introduced to determine the shortest separation distance between MV/LV substation and LV neutral grounding configurations ensuring safety against transferred potentials where common grounding is not applied. For a typical MV/LV substation a safety curve is specified relating ground fault current parameters and soil resistivity to the shortest permissible distance between the separate grounding configurations of the MV/LV substation and LV neutral.

The use of the proposed methods is demonstrated through an application to typical 20/0.4 kV substations of the Hellenic distri-

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bution system. The employed safety criteria are according to IEEE Std 80 [1] and CENELEC EN 50522 [7].

2. Safety performance evaluation

Safety performance evaluation of a grounding system can be accomplished by either analytical calculations [1,8–10], for rather simple ground electrode configurations, or computations using grounding analysis software. Both approaches require the representation of the actual soil of the installation area with a soil model, the estimation of the maximum allowable touch and step voltage limits that should not be exceeded, as well as knowledge of the ground fault current and fault duration of the worst type of ground fault causing the most hazardous conditions for persons in the vicinity of the grounding system.

2.1. Soil modeling

Soil modeling directly affects the estimation of the ground resistance, ground potential rise (*GPR*) and touch and step voltages, as well as the corresponding allowable voltage limits in case of a ground fault. It is well established that the electrical resistivity of soil varies with depth. Thus, actual soil conditions can be represented by a multilayer soil model comprising several layers characterized by their resistivity and thickness. However, according to common practice, uniform or two-layer soil models are employed in grounding system analysis [1]. For that purpose, several methods have been proposed in literature to either directly derive an approximate equivalent uniform soil model from soil resistivity measurements or approximately reduce a multilayer to a two-layer or uniform soil model [1].

In this study a uniform soil model has been adopted so as to facilitate the derivation of a straightforward safety performance evaluation method for typical MV/LV substation grounding systems. Actually, uniform soil models are most commonly used in simplified methods for grounding system design and analysis, such as that proposed in IEEE Std 80 [1].

2.2. Maximum allowable voltage limits

The maximum allowable voltage limits can be estimated according to the IEEE Std 80 [1] or CENELEC EN 50522 [7]. According to [1], the maximum allowable touch, E_{touch} (V), and step, E_{step} (V), voltages are given as:

$$E_{touch} = (1000 + 1.5C_s \cdot \rho_s)(k/\sqrt{t_s}) \tag{1}$$

$$E_{step} = (1000 + 6C_s \cdot \rho_s)(k/\sqrt{t_s}) \tag{2}$$

where t_s (s) is the duration of the electric shock current, ρ_s (Ωm) is the resistivity of the surface material, spread on the ground surface to increase the contact resistance between the ground and persons' feet, C_s (p.u.) is the surface layer derating factor given by (3) and k ($As^{0.5}$) is a factor related to tolerable electric shock energy taking values of 0.116 and 0.157$As^{0.5}$ for people weighing 50 kg and 70 kg, respectively.

$$C_s = 1 - \frac{0.09(1-\rho/\rho_s)}{2h_s + 0.09} \tag{3}$$

In (3) h_s (m) is the thickness of the surface material layer and ρ (Ωm) is the soil resistivity. If a surface material is not used then $\rho_s = \rho$ and $C_s = 1$ p.u.

According to CENELEC EN 50522 [7], the allowable touch voltage, U_{Tp} (V), is given by (4). The allowable step voltage limit is not treated, as step voltages are considered as safe if touch voltage requirements are satisfied.

$$U_{Tp} = \frac{I_B(t_f) \cdot Z_T(U_T) \cdot BF}{HF} \tag{4}$$

In (4) t_f (s) is the fault duration, I_B (A) is the body current limit, U_T (V) is the touch voltage, Z_T (Ω) is the body impedance and HF (p.u.) and BF (p.u.) are respectively the heart current and body factors. Values for the parameters of (4) are selected from IEC TS 60479-1 [11]. The effect of additional resistance, R_F (Ω), in series with the human body impedance on the allowable touch voltage limit, U_{vTp} (V), is taken into account as:

$$U_{vTp} = U_{Tp} + R_F \cdot U_{Tp}/Z_T(U_{Tp}). \tag{5}$$

R_F (Ω) is given as:

$$R_F = R_{F1} + 1.5 \cdot \rho \tag{6}$$

where R_{F1} (Ω) could be the resistance of footwear; an average resistance for old and wet shoes is 1000 Ω. The second term of (6) accounts for the resistance of the standing point to ground; ρ (Ωm) is the soil resistivity at the ground surface.

2.3. Ground fault current

Generally, the ground fault causing the highest current flowing from the grounding system to the ground does not necessarily result in the most dangerous conditions for persons inside or in the vicinity of an installation. A lower ground fault current could be more hazardous if it flows for a longer time. For an MV/LV distribution substation, MV side ground faults are typically the most dangerous ones. The maximum value of the fault current depends on the neutral grounding method [12,13] of the MV distribution system and on the impedances between the ground fault location and current source. The part of the ground fault current flowing from the grounding system to the surrounding ground, causing the *GPR* of the grounding system, depends on the available return paths of the fault current to its source. These paths, such as grounded neutral conductors, overhead ground wires and cable sheaths, reduce the *GPR* of the grounding system and therefore also the arising touch and step voltages. The duration of the ground fault occurring in an MV/LV distribution substation depends on the magnitude of the fault current and the protection scheme used, that is, the time–current characteristics of the protective devices.

2.4. Safety performance evaluation procedure

For a grounding system safety is ensured if the maximum touch, $V_{t(max)}$ (V), and step, $V_{s(max)}$ (V), voltages arising in the area of concern in case of a ground fault are lower than the corresponding allowable touch, $V_{t(lim)}$ (V), and step, $V_{s(lim)}$ (V), voltage limits. Thus, as a worst case scenario for safety evaluation:

$$V_{t(\max)} = V_{t(\lim)} \tag{7a}$$

$$V_{s(\max)} = V_{s(\lim)}. \tag{7b}$$

$V_{t(max)}$ and $V_{s(max)}$ can be expressed with reference to the ground potential rise, *GPR* (V), that is, the potential attained by the grounding configuration with respect to the remote earth:

$$V_{t(\max)} = k_t \cdot GPR \tag{8a}$$

$$V_{s(\max)} = k_s \cdot GPR \tag{8b}$$

where k_t (p.u.) and k_s (p.u.) are respectively the proportionality factors for touch and step voltages, accounting for the effect of grounding system geometry on $V_{t(max)}$ and $V_{s(max)}$, and GPR is given as:

$$GPR = I_G \cdot R_g = I_G \cdot k_g \rho. \tag{9}$$

In (9) R_g (Ω) is the ground resistance, k_g (m^{-1}) is the geometric proportionality factor, accounting for the effect of grounding system geometry on R_g, ρ (Ωm) is the soil resistivity and I_G (A) is the maximum grid current [1]:

$$I_G = D_f \cdot S_f \cdot I_f \tag{10}$$

where I_f (A) is the symmetrical ground fault current, S_f (p.u.) is the fault current division factor, which considers fault current return paths additional to the ground, and D_f (p.u.) is the decrement factor accounting for the dc offset of the fault current.

Using (9) expressions (8) become:

$$V_{t(\max)} = k_t \cdot k_g \cdot I_G \cdot \rho \tag{11a}$$

$$V_{s(\max)} = k_s \cdot k_g \cdot I_G \cdot \rho \tag{11b}$$

thus for any ground fault current and soil resistivity the maximum touch and step voltages can be easily estimated given that the proportionality factors k_g, k_t and k_s are known. These factors depend solely on grounding configuration geometry and can be calculated analytically [1,8–10] for rather simple ground electrode configurations. Alternatively, for more complex grounding configurations, they can be determined through grounding analysis software using a set of arbitrary values for ground fault current and soil resistivity.

By considering the maximum allowable voltage limits as defined in IEEE Std 80 [1], putting (1)–(3) and (11) in (7) the upper limits of soil resistivity below which safety is ensured can be expressed as a function of ground fault current and shock duration as:

$$\rho_{touch} = \frac{k(1000 + 1.5\rho_s)(2h_s + 0.09) - 1.5 \cdot 0.09k\rho_s}{k_t \cdot k_g \cdot I_G \cdot \sqrt{t_s}(2h_s + 0.09) - 1.5 \cdot 0.09k} \tag{12a}$$

$$\rho_{step} = \frac{k(1000 + 6\rho_s)(2h_s + 0.09) - 6 \cdot 0.09k\rho_s}{k_s \cdot k_g \cdot I_G \cdot \sqrt{t_s}(2h_s + 0.09) - 6 \cdot 0.09k}. \tag{12b}$$

If a high resistivity surface material is not used these expressions are simplified to:

$$\rho_{touch} = \frac{1000k}{k_t \cdot k_g \cdot I_G \cdot \sqrt{t_s} - 1.5k} \tag{13a}$$

$$\rho_{step} = \frac{1000k}{k_s \cdot k_g \cdot I_G \cdot \sqrt{t_s} - 6k}. \tag{13b}$$

In (12) and (13) the duration of the electric shock current, t_s (s), can be taken equal to the clearing time of the protective device installed upstream the fault location. The clearing time (fault duration) is a function of the ground fault current as determined by the time–current characteristic of the protective device. Hence, for a set of values of ground fault current and fault duration upper limits of soil resistivity corresponding to touch and step voltages can be found; the lower soil resistivity limit is retained. Thus, by using the full time–current characteristic of the protective device in (12) or (13) a safety performance curve can be constructed relating the expected ground fault current to the upper limit of soil resistivity below which the allowable voltage is not exceeded. Furthermore, as the ground resistance of a grounding configuration is proportional to soil resistivity, the safety performance curve may easily refer to an upper limit of ground resistance.

Following the same procedure, using the allowable touch voltage limit according to CENELEC EN 50522 (4)–(6), the upper limit of soil resistivity below which safety is ensured can be expressed as a function of ground fault current and fault duration:

$$\rho_{touch} = \frac{U_{Tp}(t_f)[Z_T(U_{Tp}) + R_{F1} + 1.5\rho_s]}{k_t \cdot k_g \cdot I_G \cdot Z_T(U_{Tp})}. \tag{14}$$

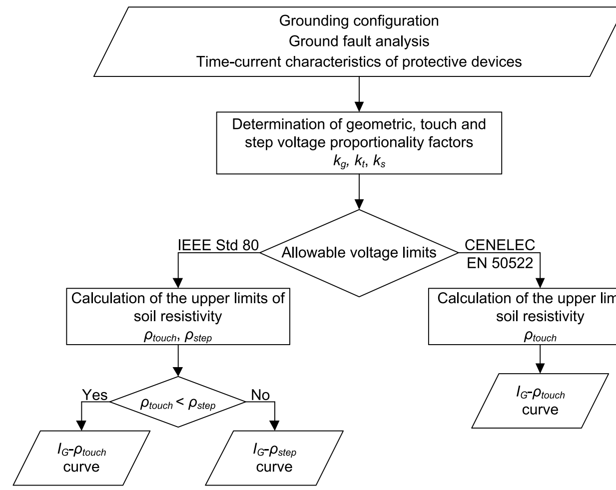

Fig. 1. Flowchart for the construction of safety performance curves.

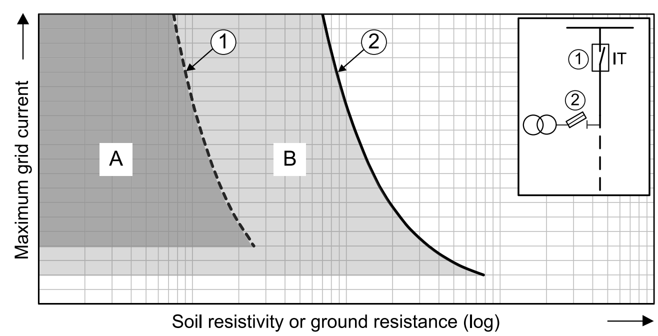

Fig. 2. Safety performance curves; (A) ground relay using an inverse time–current characteristic and (B) expulsion-type fuse.

If a high resistivity surface material is not used, ρ_{touch} becomes:

$$\rho_{touch} = \frac{U_{Tp}(t_f)[Z_T(U_{Tp}) + R_{F1}]}{k_t \cdot k_g \cdot I_G \cdot Z_T(U_{Tp}) - 1.5U_{Tp}(t_f)}. \tag{15}$$

The procedure for constructing safety performance curves is summarized in the flowchart of Fig. 1:

i. Determination of the geometric, touch and step voltage proportionality factors, either analytically or with the aid of grounding analysis software.
ii. Selection of the allowable voltage limits according to IEEE Std 80 or CENELEC EN 50522.
iii. Construction of safety performance curves $I_G - \rho$ (or $I_G - R_g$) according to either (12) and (13) for IEEE Std 80 or (14) and (15) for CENELEC EN 50522, using the time–current characteristic of the protective device installed upstream the fault location.

The above procedure is applied only once to obtain a safety performance curve specific to the evaluated typical grounding configuration and protective device. For the safety performance evaluation of an already installed or new MV/LV substation the set of values of measured soil resistivity (or ground resistance) and estimated most dangerous ground fault current is simply compared with the corresponding safety performance curve.

Such curves are shown in Fig. 2; safety is ensured if the point with coordinates corresponding to the soil resistivity (or ground resistance) and most dangerous ground fault current of the evaluated substation lies within the shaded area defined by the relevant safety performance curve. In Fig. 2 areas A and B, obtained for a ground relay using an inverse time–current characteristic and an

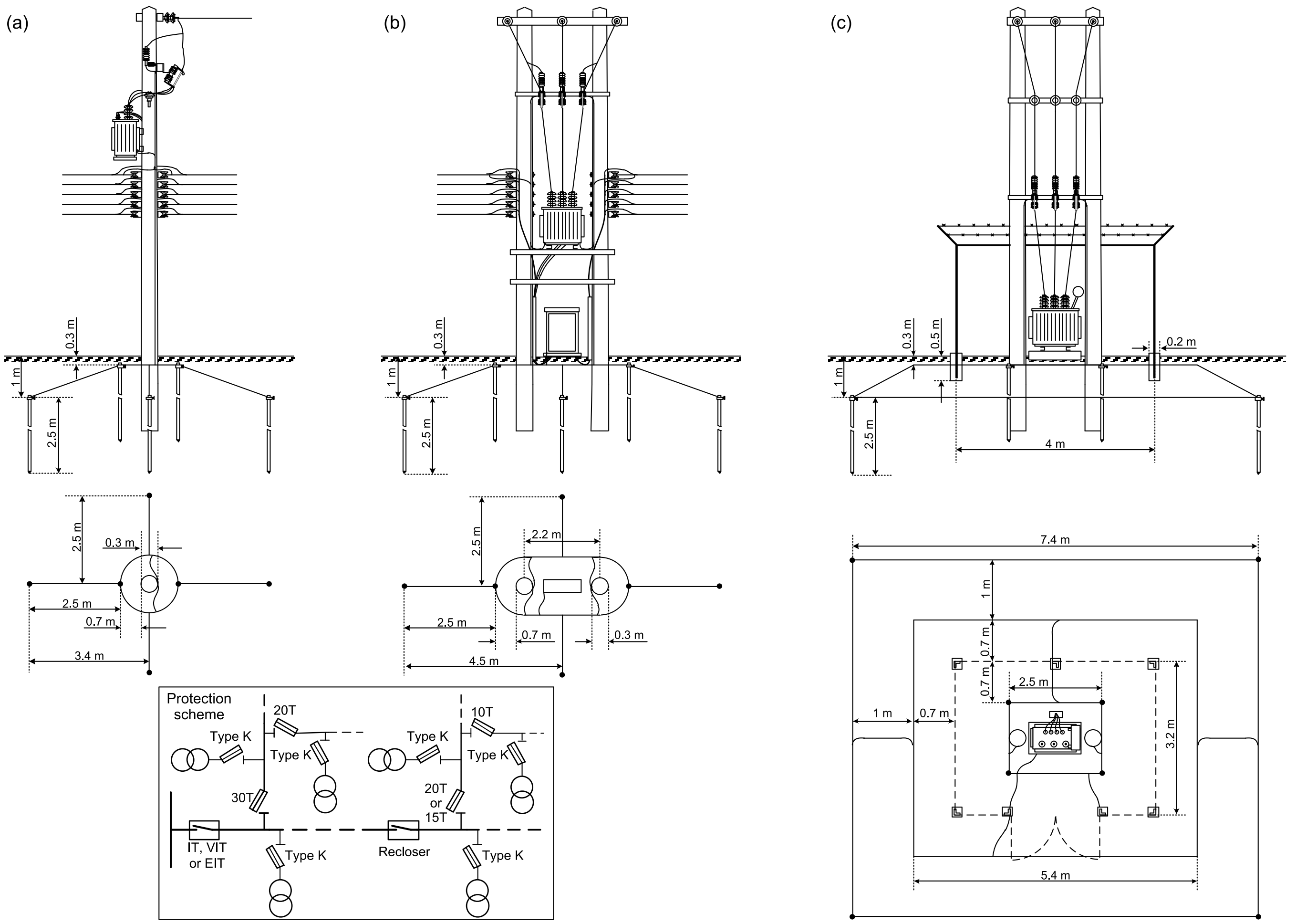

Fig. 3. Typical outdoor 20/0.4 kV substations of the Hellenic distribution system, corresponding grounding configurations and protection scheme: (a) transformer mounted on single pole, (b) transformer mounted on two poles and (c) ground-based transformer; (not according to scale).

expulsion-type fuse, refer respectively to a ground fault at the substation upstream and downstream the fuse cutout. Generally, the time–current characteristic of the protective device clearing the fault affects the shape of the safety performance curves. This is shown in the following section through an application to the typical grounding configurations used in MV/LV substations of the Hellenic distribution system.

3. Application to 20/0.4 kV distribution substations

3.1. Description of the evaluated systems

Figs. 3 and 4 show five typical 20/0.4 kV substations of the Hellenic distribution system and their corresponding grounding configurations. These substations comprise distribution transformers (winding connection: Dyn11 or Yzn11, secondary neutral solidly grounded) with rated power from 25 kVA to 1000 kVA. Outdoor substations (Fig. 3), are connected to the 20 kV overhead distribution network; depending on rated power, transformers are either ground-based or mounted on one or two, wood or concrete poles. Substations housed in prefabricated buildings (Fig. 4) are connected to the 20 kV underground cable distribution network. Currently, more than 130,000 substations, most commonly pole-mounted, are installed in the Hellenic 20 kV distribution system. Typical grounding configurations comprise tinned copper horizontal ground conductors (cross section: 35 mm^2) and copper-clad steel ground rods (diameter: 16 mm, length: 2.5 m).

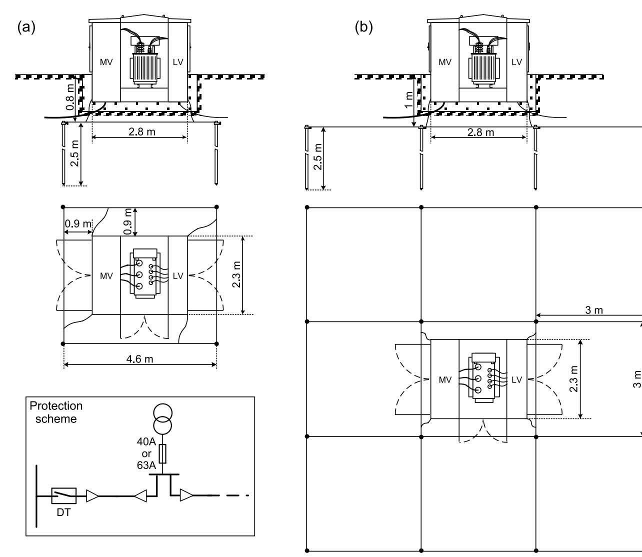

Fig. 4. Typical 20/0.4 kV prefabricated substations of the Hellenic distribution system, corresponding grounding configurations and protection scheme: (a) common and (b) separate substation and secondary neutral grounding; (not according to scale).

The worst ground fault type for the Hellenic 20 kV three-wire unigrounded distribution system is a single phase ground fault. The maximum ground fault current is limited to values lower than

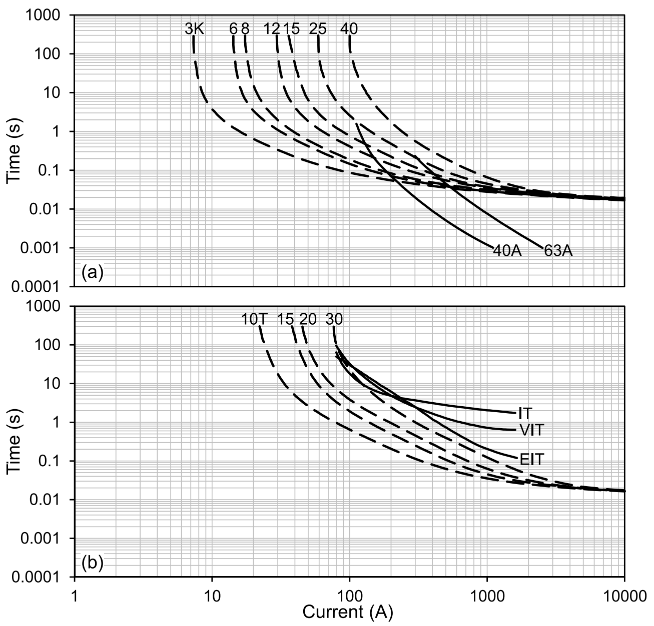

Fig. 5. Time–current characteristics of typical protective devices used in the 20 kV network of the Hellenic distribution system; (a) expulsion-type (type K) and current-limiting fuses, (b) ground relays (pickup current: 80 A) and expulsion-type fuses (type T); characteristics of expulsion-type fuses correspond to the total clearing time (pre-arcing and arcing time).

1 kA (symmetrical ground fault current) as neutral grounding of the 20 kV side of the 150/20 kV step-down transformers (winding connection: Dyn1 or YNyn0) is achieved by using 12 Ω current limiting resistors. The actual maximum ground fault current of a distribution substation depends on its distance from the 150/20 kV substation. The fault current division factor, S_f, is equal to 1 for the distribution substations fed by overhead lines, since neutral conductors and overhead ground wires are not utilized in the Hellenic overhead distribution network. For the prefabricated substations (Fig. 4) the ground fault current can return to its source through the sheaths of the 20 kV power cables; in this case typical values for S_f are 0.5–0.6 [7].

Figs. 3 and 4 include typical coordinated protection schemes utilized in the Hellenic distribution network. The 20/0.4 kV transformers of the outdoor substations are protected by fuse cutouts with expulsion-type fuses (type K) [14,15], whereas current-limiting fuses [16,17] are used in prefabricated substations; time–current characteristics are shown in Fig. 5a. The 20 kV overhead lines and cables leaving the 150/20 kV substation are protected against faults by circuit breakers controlled by relays. For the 20 kV overhead network a reclosing scheme is used; in case of a ground fault the circuit breaker initially trips instantaneously (~0.15 s) to clear temporary faults, then the instantaneous element is disabled and after the immediate reclosing operation (~0.5 s) inverse, very inverse or extremely inverse time–current characteristics (Fig. 5b) are used. It must be noted that there are also feeder circuit breakers not equipped with an instantaneous element. Overhead distribution line laterals are protected by expulsion-type fuses (type T, Fig. 5b) and reclosers where appropriate. In the 20 kV underground cable network, neither a reclosing function nor instantaneous tripping are used; ground relays have a definite time characteristic (1 s).

3.2. Safety performance evaluation

Grounding analysis for the typical grounding configurations shown in Figs. 3 and 4 was performed with the aid of the CYMGrd software [18] so as to obtain the proportionality factors k_g, k_t and k_s. According to the estimated values of the geometric factor, k_g, shown in Table 1, the ground resistance is lowest for the prefabricated substation shown in Fig. 4b; this is due to the relatively large area covered by its grounding configuration. Also, relatively high soil resistivity values would result in high ground resistance for all grounding configurations; such high resistance values have been reported in [19] for pole-mounted substations of the Hellenic distribution system.

Table 1
Grounding analysis results for the grounding configurations of the typical 20/0.4 kV substations shown in Figs. 3 and 4.

20/0.4 kV substation	Geometric factor k_g (m^{-1})	Touch voltage factor k_t (p.u.)
Transformer on single pole (Fig. 3a)	0.080	0.184
Transformer on two poles (Fig. 3b)	0.072	0.164
Ground-based transformer (Fig. 3c)	0.050	0.116
Prefabricated substation, common neutral grounding (Fig. 4a)	0.076	0.292
Prefabricated substation, separate neutral grounding (Fig. 4b)	0.039	0.106

It is important that safety can be achieved even for high ground resistances [1,4] if appropriate measures are taken. However, a high ground resistance causing low ground fault currents may compromise the protection of the MV system. The lightning performance of the distribution transformer may be adversely affected as well. Lightning overvoltage surges traveling on the MV overhead line and impinging on the transformer stress more severely the LV side of the transformer in case of high ground resistance [20,21]. According to field observations [19,22], lightning-caused distribution transformer failures are generally associated with high values of ground resistance.

As expected, for all evaluated substations the upper limit of soil resistivity below which safety is ensured, as determined by (12) and (13), was found lower for touch than step voltage. Thus, the safety performance evaluation results that follow refer solely to touch voltage; the corresponding touch voltage factors, k_t, for all substations are listed in Table 1.

Fig. 6 shows safety performance curves for the case of a single pole mounted transformer (Fig. 3a). These curves were calculated with the aid of (12) and (13) using the time–current characteristics of the coordinated protective devices (Fig. 5) installed in the overhead distribution network shown in the inset of Fig. 6a; the feeder circuit breaker is not equipped with an instantaneous element. The curves consider shock durations <3 s, as dictated by the allowable touch and step voltage limits according to IEEE Std 80 [1].

As evident in Fig. 6, the highest limits of soil resistivity are obtained for the time–current characteristic of the 3K expulsion-type fuse protecting the transformer due to the shorter fault clearing time. For ground faults at the substation occurring upstream the fuse cutout, the upper limits of soil resistivity are determined by the time–current characteristics of the protective device installed closer to the substation. The application of a high resistivity surface material around the substation can easily be considered in the construction of the safety performance curves by using (12) (Fig. 6b).

As an example, let us consider a single pole mounted substation (Fig. 3a) with $I_{G,max}$ = 500 A and ρ = 100 Ωm (R_g = 8 Ω) corresponding to point A in Fig. 6. For this substation safety is ensured against the most common ground faults occurring downstream the fuse cutout; this is because point A in Fig. 6a lies within the shaded area defined by the safety performance curve corresponding to the 3K expulsion-type fuse. However, this is not the case for a single pole mounted substation with $I_{G,max}$ = 500 A installed in an area with ρ = 200 Ωm (R_g = 16 Ω) (point B in Fig. 6a). In this case, safety is

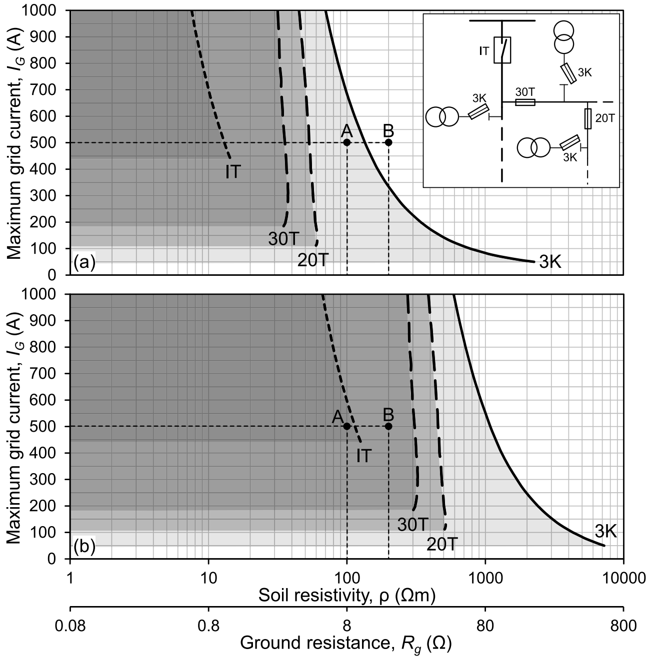

Fig. 6. Safety performance curves for the typical grounding configuration of the single pole mounted 20/0.4 kV transformer (Fig. 3a); allowable limits according to IEEE Std 80 (body weight 70 kg, S_f = 1); (a) without and (b) with surface material (asphalt): ρ_s = 10,000 Ωm, h_s = 0.05 m.

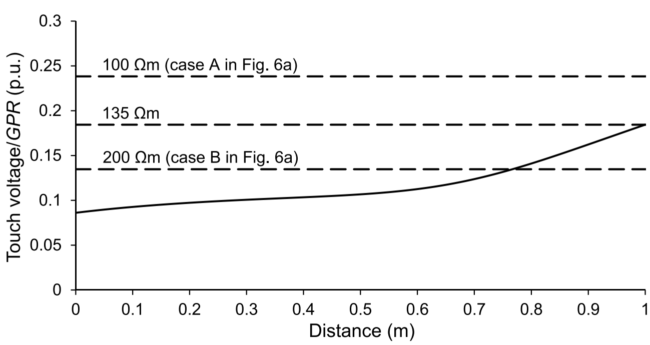

Fig. 7. Variation of the touch voltage along the critical profile with the highest touch voltage values for the case of the single pole mounted 20/0.4 kV transformer shown in Fig. 3a; increasing distance from the pole; dashed lines denote the normalized allowable touch voltage limits for the example cases of Fig. 6a (points A and B).

achieved if asphalt is applied as a high resistivity surface material (Fig. 6b).

The results of the application of the proposed methodology to the example cases of substations A and B of Fig. 6a are validated with the aid of grounding analysis software [18] in Fig. 7. This figure shows for the case of the single pole mounted 20/0.4 kV transformer of Fig. 3a the variation of the touch voltage (normalized with respect to *GPR*) with the distance from the pole along the critical profile with the highest touch voltage values. Fig. 7 also includes the normalized allowable touch voltage limits corresponding to points A (ρ = 100 Ωm, $I_{G,max}$ = 500 A) and B (ρ = 200 Ωm, $I_{G,max}$ = 500 A) of Fig. 6a. These limits were obtained from (1) by using the fault clearing time of 0.036 s derived from the time–current characteristic of the 3K expulsion-type fuse for $I_{G,max}$ = 500 A (Fig. 5a). As evident in Fig. 7, safety is ensured for substations installed at sites with soil resistivity lower than 135 Ωm; the latter value can be easily deduced from the safety performance curve corresponding to the 3K expulsion-type fuse as shown in Fig. 6a.

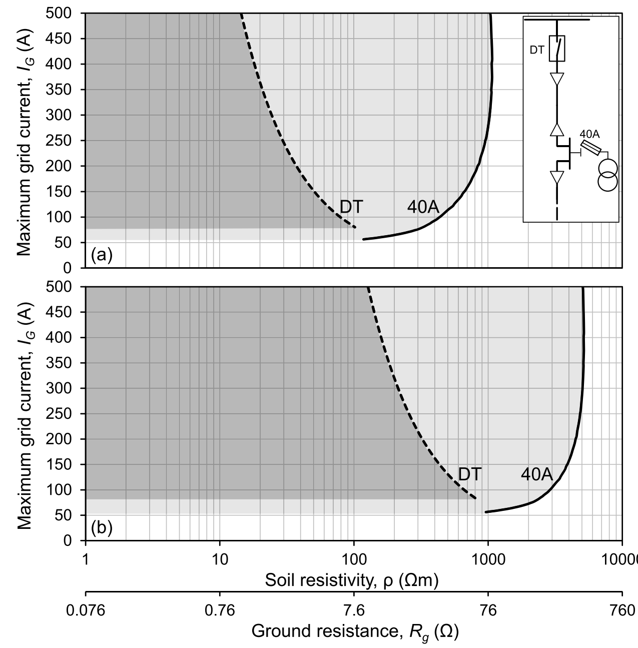

Fig. 8. Safety performance curves for the typical grounding configuration of the prefabricated 20/0.4 kV substation (Fig. 4a); allowable limits according to IEEE Std 80 (body weight 70 kg, S_f = 0.5); (a) without and (b) with surface material (asphalt): ρ_s = 10000 Ωm, h_s = 0.05 m.

Fig. 8 shows safety performance curves for the prefabricated substation of Fig. 4a with and without using a very high resistivity surface material. It is important that the shape of the curves is affected by the time–current characteristic of the protective device clearing the fault and the grounding system geometry (Figs. 6 and 8). Also, Fig. 8 provides evidence that the most severe ground fault is not always associated with the highest fault current; based on the time–current characteristic of the 40 A current-limiting fuse the upper limit of soil resistivity decreases as the fault current decreases. This clearly shows that both maximum and minimum expected fault currents shall be considered for the safety performance evaluation of a grounding system.

Fig. 9 shows a comparison between safety performance evaluation curves obtained using the allowable voltage limits according to IEEE Std 80 [1] and CENELEC EN 50522 [7]. These curves refer to the case of the distribution transformer mounted on two poles shown in Fig. 3b considering for simplicity only a 6K expulsion-type fuse protecting the transformer. The IEEE Std 80 generally poses more stringent requirements as compared with CENELEC EN 50522; however, this depends on fault duration as determined by the time–current characteristic of the protective device.

4. Separation distance between MV/LV substation and secondary neutral grounding configurations

In LV distribution systems with distributed neutral conductor care should be taken to prevent the transfer of hazardous potentials through the neutral in case of an MV side ground fault at the MV/LV distribution substation [1,7,23]. Transferred potentials may pose a threat to persons as well as to the insulation of LV system equipment.

Common or separate grounding can be applied between the MV and LV sides of a distribution substation depending on the *GPR* of the MV grounding system. In the case of separate grounding, the separation distance between MV/LV substation and LV neutral grounding configurations shall be long enough to avoid coupling through the ground. This separation distance depends on

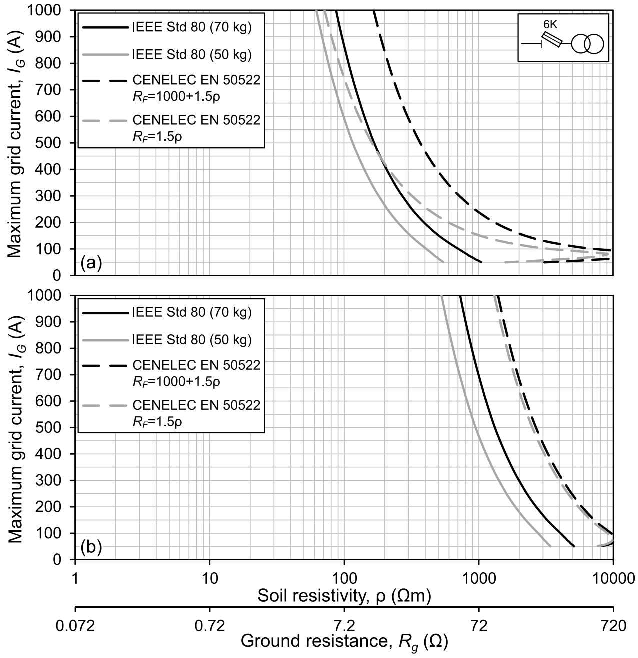

Fig. 9. Safety performance curves for the typical grounding configuration of the 20/0.4 kV transformer mounted on two poles (Fig. 3b); allowable limits according to IEEE Std 80 and CENELEC EN 50522; S_f = 1; (a) without and (b) with surface material (asphalt): ρ_s = 10000 Ωm, h_s = 0.05 m.

soil conditions, ground fault characteristics and grounding configurations geometry. However, most commonly, a fixed distance is used between the separate grounding configurations. In overhead LV distribution systems the neutral is commonly grounded at the first line pole after the MV/LV substation, that is, at a distance of ~50–100 m. This distance is significantly shorter for underground LV distribution systems.

4.1. Maximum allowable voltage limits

In LV installations safety against transferred potential is certainly ensured if the arising touch voltages are limited to values lower than the maximum allowable metal-to-metal touch voltage limit, $E_{mm\text{-}touch}$ (V); the latter is given according to IEEE Std 80 [1] as:

$$E_{mm\text{-}touch} = \frac{1000k}{\sqrt{t_s}} \tag{16}$$

where t_s (s) and k (As$^{0.5}$) are defined in (1) and (2). As a worst case, for TN systems, $E_{mm\text{-}touch}$ shall not be exceeded by the *GPR* of the common grounding system or the *GPR* attained by the neutral ground electrode due to coupling through the ground where separate grounding is applied.

According to CENELEC EN 50522 [7], common grounding is applied where a “global earthing system” exists. Alternatively, minimum requirements regarding touch voltage and voltage stressing LV equipment, depending on the type of LV system (Table 2 of [7]), have to be satisfied. If this is not the case, the secondary neutral shall be grounded separately from the MV/LV substation grounding configuration.

Touch voltages are considered to be safe if the *GPR* of the common grounding system or the *GPR* attained by the neutral ground electrode due to coupling through the ground does not exceed the voltage limit, V_{lim} (V) [7]:

$$V_{\lim} = FU_{Tp} \tag{17}$$

where U_{Tp} (V) is given by (4) and F (p.u.) is a constant taking values between 1 and 5 p.u. A typical value of F is 2 p.u. for a neutral conductor with multiple connections to the ground [7,23]. If the neutral conductor is only grounded at the MV/LV substation F = 1 p.u. [7].

The maximum *GPR* limits for the voltage stressing LV equipment depend on fault duration, t_f [7,23]:

$$V_{\lim} = 1200\,\text{V}, \quad t_f \le 5\,\text{s} \tag{18a}$$

$$V_{\lim} = 250\,\text{V}, \quad t_f > 5\,\text{s}. \tag{18b}$$

4.2. Procedure for the estimation of the minimum required separation distance

The following procedure can be applied to estimate the shortest separation distance between typical MV/LV substation and LV neutral grounding configurations ensuring safety in LV installations. Initially, the critical profile along an increasing distance from the substation grounding configuration with the highest surface potential values is determined. These values are considered as upper limits of the potential arising at the LV neutral ground electrode. The surface potential, V_{sp} (V), along the critical profile can be expressed with reference to *GPR* (V) as:

$$V_{sp}(x) = k_{sp}(x) \cdot GPR \tag{19}$$

where $k_{sp}(x)$ (p.u.) is the surface potential proportionality factor expressed as a function of separation distance, x (m), accounting for the effect of grounding system geometry on V_{sp}.

Using (9) expression (19) becomes:

$$V_{sp}(x) = k_{sp}(x) \cdot k_g \cdot I_G \cdot \rho \tag{20}$$

thus, the surface potential values along the critical profile can be easily calculated for any ground fault current and soil resistivity given that k_g (m^{-1}) and $k_{sp}(x)$ (p.u.) are known. These proportionality factors can be calculated analytically [8–10] or with the aid of grounding analysis software depending on the complexity of the grounding configuration.

For the evaluated MV/LV substation and LV neutral grounding configurations safety is ensured for a separation distance longer than that corresponding to a surface potential equal to the allowable voltage limit. Touch voltages need no consideration in TT LV systems; the same applies for transferred voltages stressing equipment in TN LV systems.

For TN systems the critical separation distance, x_{cr} (m), that is, the shortest separation distance ensuring safety, can be estimated using the following equation:

$$V_{sp}(x_{cr}) = E_{mm\text{-}touch} \tag{21}$$

considering the maximum allowable metal-to-metal touch voltage limit, $E_{mm\text{-}touch}$ (V), as given by (16) according to IEEE Std 80 [1]. Thus, using (16) and (20) in (21):

$$(I_G\sqrt{t_s})\rho = \frac{1000k}{k_{sp}(x) \cdot k_g} \tag{22}$$

hence, a limiting curve can be constructed relating the product $(I_G\sqrt{t_s})\rho$ (As$^{0.5}$ Ωm) to separation distance, x (m); this curve is specific to the evaluated typical grounding configurations. For a given value of the product $(I_G\sqrt{t_s})\rho$, which depends on ground fault current and installed protective device as well as soil conditions, the critical separation distance can be estimated easily by using the corresponding limiting curve.

Following the same procedure, considering the allowable voltage limit (17) according to CENELEC EN 50522 [7] and IEC 60364-4-44 [23] the following expression can be used for the

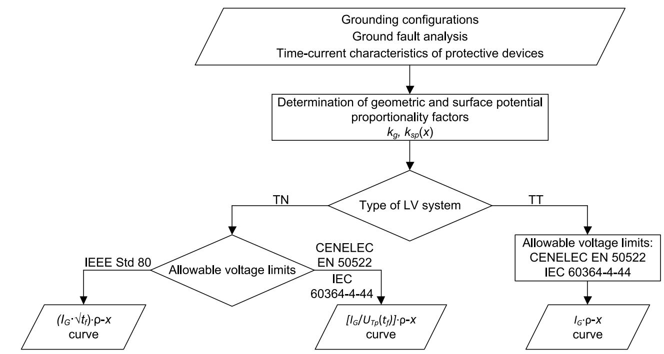

Fig. 10. Flowchart for constructing safety curves for the estimation of the critical separation distance between MV/LV substation and LV neutral grounding configurations.

determination of the separation distance ensuring safety against transferred potentials in TN systems:

$$\left(\frac{I_G}{U_{Tp}(t_f)}\right)\rho = \frac{F}{k_{sp}(x)\cdot k_g}. \qquad (23)$$

Thus, a limiting curve can be constructed relating quantity $(I_G/U_{Tp})\rho$ (A Ωm/V) to separation distance, x (m).

For TT LV systems, the same procedure is applied for the allowable voltage limits expressed by (18). The separation distance ensuring safety against transferred potentials can be determined from the following equations:

$$I_G\cdot\rho = \frac{1200}{k_{sp}(x)\cdot k_g}, \quad t_f \le 5\,\text{s} \qquad (24a)$$

$$I_G\cdot\rho = \frac{250}{k_{sp}(x)\cdot k_g}, \quad t_f > 5\,\text{s}. \qquad (24b)$$

By using (24) upper limits of $I_G{\cdot}\rho$ (A·Ωm) can be estimated as a function of separation distance, x (m).

The procedure to construct safety curves for the estimation of the critical separation distance between MV/LV substation and LV neutral grounding configurations is described in steps, according to the flowchart of Fig. 10, as follows:

i. Determination of the geometric and surface potential proportionality factors, either analytically or with the aid of grounding analysis software.
ii. Depending on the type of LV system:
   a. For TN systems selection of the allowable voltage limits according to IEEE Std 80 or CENELEC EN 50522 and IEC 60364-4-44.
   b. For TT systems allowable voltage limits are according to CENELEC EN 50522 and IEC 60364-4-44.
iii. Construction of safety curves:
   a. For TN systems $(I_G\sqrt{t_s})\rho - x$ curves according to (22) for IEEE Std 80, or $(I_G/U_{Tp})\rho - x$ curves according to (23) for CENELEC EN 50522 and IEC 60364-4-44.
   b. For TT systems $I_G{\cdot}\rho - x$ curves according to (24) for CENELEC EN 50522 and IEC 60364-4-44.

The above procedure is applied only once for typical grounding configurations. Then, for the estimation of the minimum required distance between the separate grounding configurations, the values of measured soil resistivity and the estimated most dangerous ground fault current as well as its duration are simply used along with the safety curve.

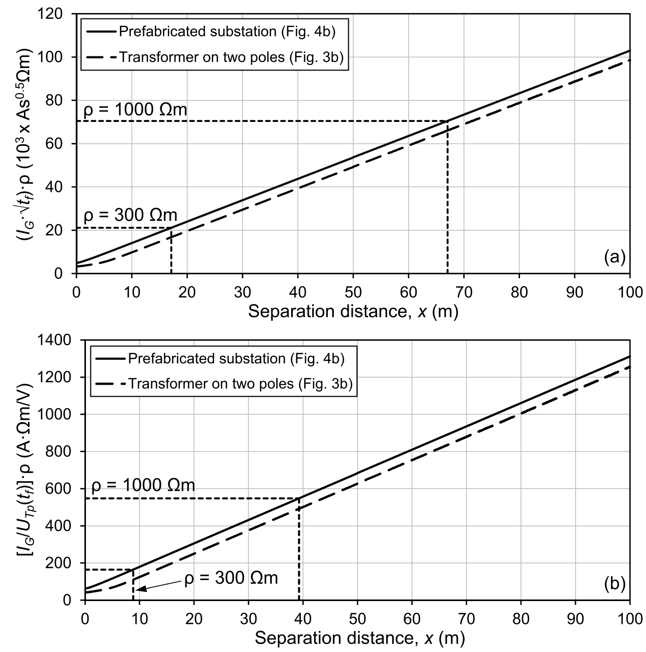

Fig. 11. Safety curves for the determination of the critical separation distance between MV/LV substation and LV neutral grounding configurations; allowable limits according to (a) IEEE Std 80 (body weight 70 kg) and (b) CENELEC EN 50522; examples refer to: S_f = 0.5 and current-limiting fuse 40 A.

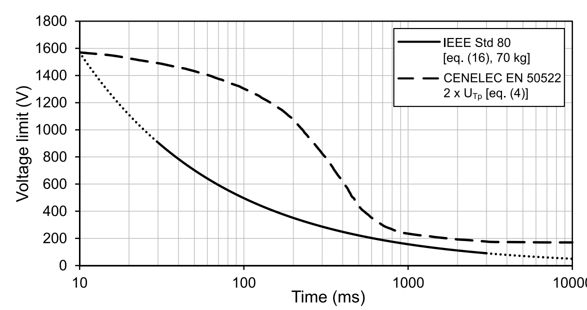

Fig. 12. Voltage criteria for safety evaluation against touch voltages due to transferred potentials through the LV system neutral.

4.3. Application to 20/0.4 kV distribution substations feeding a TN LV system

Results on typical 20/0.4 kV substations feeding a TN LV system are shown in Fig. 11. For a given soil resistivity the critical separation distance between MV/LV substation and LV neutral grounding configurations is found by using the maximum value of the product $I_G\sqrt{t_s}$ or ratio I_G/U_{Tp} as determined by the time–current characteristic of the protective device. As an example, when the allowable voltage limit according to IEEE Std 80 is used (Fig. 11a), for the prefabricated substation of Fig. 4b and for soil resistivity values of 300 and 1000 Ωm safety against transferred potential is ensured for separation distances longer than the critical distances of 17 m and 67 m, respectively. These critical distances are 9 m and 39 m when the CENELEC EN 50522 [7] safety criteria are applied (Fig. 11b); this behavior can be attributed to the higher allowable limits against transfer potentials for the CENELEC EN 50522 [7] than the IEEE Std 80 [1] as shown in Fig. 12.

It is important that the results of Fig. 11 do not justify the common practice of using a fixed separation distance between the MV/LV substation and LV neutral grounding configurations. The critical separation distance shall always be determined, ensuring thus safety against dangerous transferred potentials through the LV neutral.

5. Conclusions

A method has been introduced for the straightforward safety assessment of typical grounding configurations of MV/LV distribution substations, implementing safety criteria according to IEEE Std 80 or CENELEC EN 50522. The method uses a safety performance curve, specific to the evaluated grounding configuration and installed protective device, relating ground fault current to upper limits of soil resistivity, thus also ground resistance, that ensure safety. For an already installed or new MV/LV distribution substation safety performance is evaluated simply through a comparison of the corresponding safety performance curve with the set of values of measured soil resistivity (or ground resistance) and estimated most dangerous ground fault current.

In addition, a method has been introduced for the determination of the critical separation distance between MV/LV substation and LV neutral grounding configurations ensuring safety against transferred potentials through the LV system neutral. The method considers the measured soil resistivity and estimated most dangerous ground fault of the evaluated substation along with a corresponding safety curve; the latter relates ground fault current parameters and soil resistivity to critical separation distance. The use of a fixed separation distance where common grounding between MV/LV substation and LV neutral is not applied could result in dangerous potentials transferred to LV installations.

The proposed methods can also be applied for the straightforward safety performance evaluation of installations other than MV/LV distribution substations, which often utilize typical grounding systems. Such installations include transmission line towers, distribution line poles as well as consumer prefabricated MV/LV substations.

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