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Ground Fault Current Distribution When a Ground Fault Occurs in HV Substations Located in an Urban Area

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Abstract—The paper presents a method of determination of ground fault current distribution when HV (high voltage) substations are located in urban or suburban areas, or where many relevant data necessary for determination of this distribution are uncertain or completely unknown. The problem appears as a consequence of the fact that many of urban metal installations are situated under the surface of the ground and cannot be visually determined or verified. On the basis of on-the-site measurements, the developed method enables compensating all deficiencies of the relevant data about metal installations involved with the fluctuating magnet field appearing around and along a feeding power line during an unbalanced fault. The presented analytical procedure is based on the fact that two measurable quantities, currents in one phase conductor and in one neutral line conductor, cumulatively involve the inductive effects of all, known and unknown surrounding metal installations. Once, this quantity has been determined, the problem of determination of different parts of a ground fault current becomes solvable by using a relatively simple calculation procedure. The presented quantitative analysis indicates at the benefits that can be obtained by taking into account the presence of surrounding metal installations.

1. INTRODUCTION

During a ground fault in a HV network the ground fault current leaves phase line conductor and for returning to the feeding sources uses all available paths, including those that are not foreseen for this purpose. Because of that, each ground fault current in an HV network has at least two important components. One of them is injected into surrounding earth through the grounding system of a supplied substation, while the other returns to the source of origin through the neutral conductor(s) of the feeding line [1]. The first one produces all potentials and potential differences (touch and step voltages) relevant for estimation of the safety conditions in the grounding system of a supplied substation, while the other causes thermal stress on the neutral conductor(s) of the feeding line. Thus, a correct estimation of the ground fault current distribution is of the prime importance for at least two reasons, for correct designing of the grounding system of a supplied substation and correct selection of the feeding line neutral conductor(s).

With the aim of expressing the influence of different return paths on the ground fault current distribution, a special feeding line parameter is introduced in the professional literature, including technical standards [2]. This parameter is called the reduction factor of the feeding line and is defined as the ratio of the part of the ground fault current returning through earth and the total ground fault current. This definition involves the assumption that the grounding impedances of the substations at the ends of the feeding line are negligible (e.g., [2]). Under this assumption, the fault current in the neutral conductor(s) is a consequence solely of inductive coupling between this/these conductor(s) and the phase conductor through which the total ground fault current passes.

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The influence of the earth on conductor impedances has been investigated since 1926 [3, 4], while investigation of the problem of determination of ground fault current distribution continuously lasts at least five decades [5].

The firstly developed methods for solving this problem are related to the case when the feeding line is constructed as an overhead line [5–7]. Somewhat later, the papers considering this problem in special cases, when a feeding line appears as a longitudinal combination of one cable and one overhead section, have been published, e.g., [8–10]. Also, several methods have been developed for solving this problem in cases where, because of a high local soil resistivity and/or a high short-circuit level, special measures aimed at reducing part of the ground fault current flowing exclusively through the earth (e.g., bare copper conductor laid in the same trench as the cable feeding line, counterpoises, etc.) are considered indispensable [11, 12].

Then, the method developed for determination of the ground fault current distribution when a feeding cable line is constructed of three single-core cables was presented [13]. The developed method enables taking into account participation of all three metal sheaths in the ground fault current distribution for a fault at anywhere along the line.

The common characteristic of the mentioned methods is that they enable taking into consideration only the design/constructive characteristics of the feeding line and the characteristic of the surrounding earth as a conductive medium. None of the mentioned methods enables obtaining the solution of the problem when it appears in urban and suburban conditions, or when many other metal installations participate in the ground fault current returning to the power system. In such conditions each power line becomes a very complex electrical circuit with many conductively and inductively coupled elements having uncertain or completely unknown relevant data.

The problem of determination of the influence of metal installations surrounding a feeding distribution line on the ground fault current distribution through the grounding system of a supplied substation is considered in [14]. The solution is achieved by substituting all surrounding metal installations by one, from the stand point of the ground fault current distribution, equivalent conductor of cylindrical form placed around and along the considered feeding line. Somewhat later, the achieved solution was extended to include the overhead distribution lines [15].

The investigation results presented in [14, 15] show that fraction of the ground fault current flowing through the earth, in typically urban environments, is three to five times smaller than it has been considered earlier. The developed method enables a new insight into the whole grounding problem of urban HV/MV substations and dramatically changes our perception about the magnitude of this problem. It can now be seen in a realistic framework generally leading to solutions that are in accordance with the real needs, i.e., without any redundant expenditure.

The developed method simultaneously gives possibility of solving another important problem of the current engineering practice. This is the problem of determination of the line series impedance without ignoring the surrounding metal installations. Namely, these installations act as an additional neutral conductor of each distribution line passing through urban or suburban areas and, in accordance with this, its transfer characteristics are improved [16].

However, this method does not offer the possibility of determination of the part of the ground fault current passing through any of the surrounding metal installations individually. It practically means that one has no insight into the magnitude of each of these currents. Therefore, dangerous current(s) can appear(s) without our knowledge and/or control at public places which are too distant from an HV distribution substation, thus can be exposed to direct contact by humans.

The inductive influence of an HV line on an exposed metal installation can be estimated by using the current technical guide in this field [17]. However, it cannot take into account the influence of other surrounding metal installations typical for urban areas. A rigorous solution for the electromagnetic field of underground conductors and a two-layer earth is presented in [18, 19]. However, it also cannot be practically applied to the cases of an HV power line passing through urban areas.

This problem is resolved here by improving the method presented in [14, 15]. It has been done by introducing one new equivalent conductor involving the influences of all, conductively and inductively coupled surrounding metal installations. This conductor represents the equivalent neutral conductor of the feeding line and it substitutes all surrounding metal installations, including the line neutral conductor(s). On the basis of this conductor, any practical situation, from the standpoint of inductive influence of a feeding power line, becomes essentially simplified and solvable. The developed method is based on the here defined on the spot measurements and the well known analytical expression for self- and mutual impedances of a line conductor laid in the semi-infinite and homogenous earth, e.g., [2]. It enables determination of the ground fault current part which is in urban conditions induced in any of the surrounding metal installation, provided that its technical characteristics and space disposition with respect to the considered HV distribution line are known. Since the ground fault current in an HV distribution network can be greater than 20 kA, in some cases current in one of the installations deserves to be separately considered. Also, certain improvement of the calculative part of the method presented in [14, 15] is made. This improvement enables more direct and simpler calculation of the actual ground fault current fraction dissipated, through the grounding system of the supplied substation, into the surrounding earth.

2. PROBLEM DESCRIPTION

The ever increasing sizes of modern distribution networks, as well as the higher operating and short-circuit currents of these networks, have been matched by over-spreading networks of earth return circuits (different pipelines, different cable and overhead line neutrals, etc.) in close vicinity of the HV distribution lines. Spatial dispositions of all of these installations, which are determined mainly by dispositions of city streets, and small mutual distances result in the inductive and, in the vicinity of substations, conductive couplings of different network types.

The usage of common routes (mainly street pavements) for various supply networks (electricity, water, gas, oil, telecommunications, etc.) unavoidably leads to the appearance of their mutual interaction that should be determined in each concrete case. The whole problem has at least three different aspects important for current engineering practice. They are:

- determination of the fault current dissipated into the surrounding earth through the grounding system of a supplied substation [14, 15],
- determination of the influence of the surrounding metal installations on the transfer characteristics of power lines passing through urban and suburban areas [16], and
- determination of inductive influence of an HV power line on any of the surrounding individual metal installations, separately.

The first, practical difficulty stems from the fact that one of the main parameters necessary for estimation of these mutual interactions, soil resistivity of the surrounding area, cannot be determined exactly. Although there are several methods of measuring soil resistivity [1], no one of them is applicable in urban conditions. The reason for this comes from the fact that surfaces of urban areas are already covered by buildings, streets, pavements, and many other permanently constructed objects; while under the ground surface many known and unknown metal installations are laid.

Many urban metal installations of different basic functions are usually situated in a relatively closed space, like: sheaths of different types of cable lines, neutral conductors of the low voltage network, steel water pipes, building foundations, etc.. Some of them are not in direct contact with the earth, while the others are in an effective and continuous contact with the earth. They are interconnected and their spatial dispositions are different in each particular case and vary along any of the distribution lines. Also, most of them are laid under the street pavements and many relevant data about them cannot be visually determined or verified.

Grounding system of a distribution HV/MV substation consists of the substation grounding electrode and many outgoing MV cable lines acting as external grounding electrodes, and/or conductive connections with the grounding systems of the supplied MV/LV (low-voltage) substations [20]. The spontaneously formed grounding system involves a large urban area around an HV/MV substation. Such grounding system includes, through the terra-neutral (TN) grounding system in the LV network and consumer installations, many, known and unknown, metallic installations typical for an urban area. As a consequence, the outgoing cable lines simultaneously become conductive connections with metal installations laid along the same street(s) as the feeding line. Thus, it is not difficult to imagine that in the case of unbalanced operating conditions two, essentially different, currents appear out of the power system. One of them is dissipated through the grounding system of the supplied substation into the

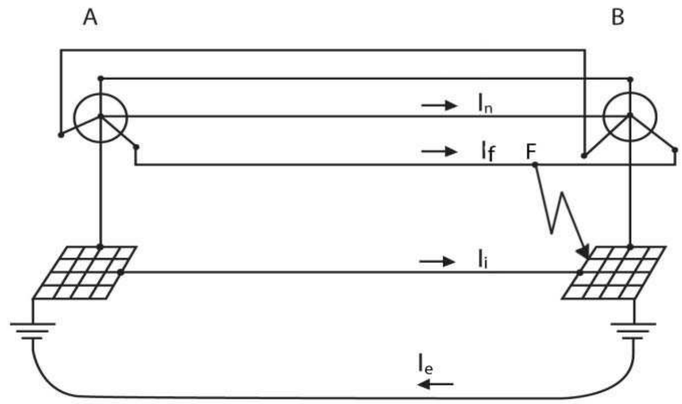

Figure 1. Main parts of the ground fault current.

surrounding earth, while the other is induced in the metal installations surrounding the feeding line. As an illustration, these two ground fault current fractions, separated by passing through the supplied substation grounding system, when a fault occurs in the substation supplied by an HV line are presented in Fig. 1.

The used notation has the following meaning:

A — supply substation,

F — ground fault (supplied substation),

I_f — ground fault current,

I_n — ground fault current component circulating through the line neutral conductor(s),

I_i — ground fault current component induced in the metal installations surrounding the feeding line, and

I_e — ground fault current component injected into the surrounding earth.

Both of the presented ground fault current fractions leave power system through the elements of the grounding system of the supplied substation, B. Current, I_e, is injected into the earth, while the other, I_i, circulates through the surrounding metal installations constructed for some other purposes. Because of that, all potentially dangerous and harmful influences of the HV power lines and supplied substations on their environments originate from these two currents. Accordingly, determination of these two currents is of prime importance when estimating the safety conditions within and in the vicinity, of the supplied substation(s) and inductive influence of a feeding line on the neighboring parallel circuits (pipeline, telecommunication line, etc.). As is well-known more sensitive electronic systems face an increasingly hostile electromagnetic environment. Magnetic coupling is an increasingly frequent cause of problems when it upsets data transmission; it requires close attention to inductance of circuit loops.

Since the process of splitting to these two current fractions occurs along many external grounding electrodes and under the surface of the ground, none of these components can be separated and determined by direct or indirect measurements [14, 15].

Each of the metal return paths, together with earth as the common return path, forms one electrical circuit, while all the metal return paths together form a large number of conductively and inductively coupled electrical circuits. Thus, the problem is: how to determine any of the currents induced in these circuits? Since for all these circuits, on the basis of Kirchhoff's laws, one can write the corresponding system of equations with currents as unknown quantities, and since the analytical expressions necessary for the self- and mutual impedances of different type of conductors are known (e.g., [2]), it can be said that the formerly defined problem has been, in principle, solvable long ago. However, because of many practical difficulties, i.e., many uncertain and unknown relevant data necessary for determination the self and mutual impedances of these circuits, this problem remained long time without any acceptable solution, [2, 17]. Thus, it can be also defined in the following way: how to find the method enabling the compensation of the objective deficiency of a huge number of relevant data?

3. THEORETICAL FOUNDATIONS OF THE METHOD

It is clear that each power line passing through urban and/or suburban areas during a ground fault represents a very complex electrical circuit. This circuit consists of a large number of mutually conductively and inductively coupled electrical circuits with common return path through the earth. The number of these circuits, if the phase line conductors are excluded, is equal to the number of the neutral line conductors enlarged by the number of surrounding metal installations.

With the aim of considering the complete line equivalent circuit, it is assumed that the cable line is performed by three single-core cables (the line having the largest number of neutral conductors) with metal sheaths grounded at the line ends. If the total number of surrounding metal installations, including the cable metal sheaths, is equal to an arbitrary number N, and if the ground fault is simulated in the supplied substation, the assumed line can be represented by the equivalent circuit shown in Fig. 2.

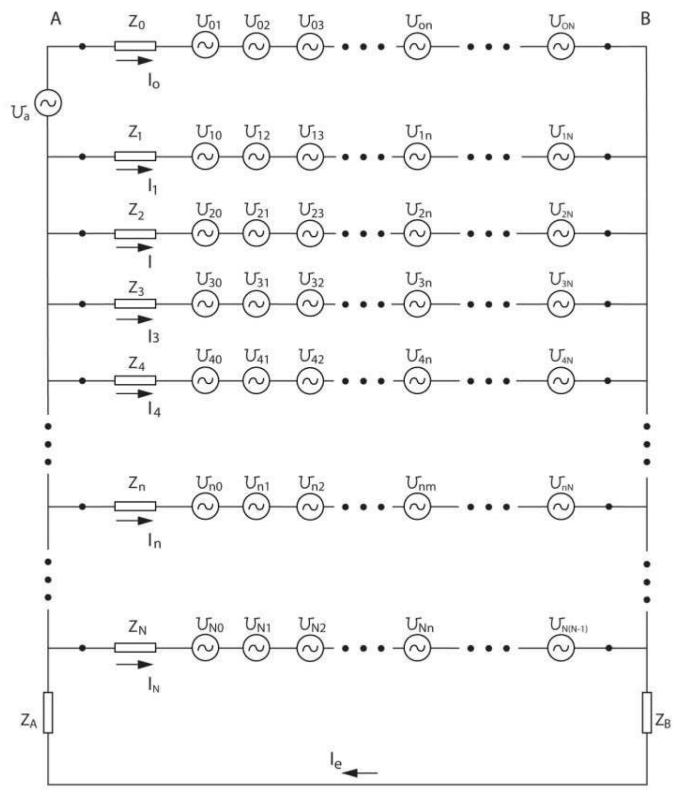

Figure 2. The complete line equivalent circuit.

The used notation has the following meaning:

U_0 — auxiliary voltage source,

U_{n0}, U_{n1}, U_{n2}, ..., U_{nN} — voltages induced in an arbitrary (n-th) circuit (metal installations) by the current in each of the surrounding circuits,

I_0 — simulated ground fault current through the phase conductor of the assumed line,

I_1 — current through the sheath of the cable carrying current I_0,

I_2, I_3 — currents through the metal sheaths of the other two single core cables,

I_4, I_5, ..., I_n, ..., I_N — currents induced in the individual surrounding metal installations,

Z_0 — self-impedance of the phase conductor of the assumed line,

Z_1, Z_2, Z_3 — self-impedances of the cable metal sheaths, and

Z_4, Z_5, Z_6, ..., Z_N — self-impedances of the individual surrounding metal installations.

An arbitrary current presented in Fig. 2, I_n, induces in an also arbitrary (mth) circuit voltage, U_{mn}, which is in general case determined by

$$U_{mn} = Z_{mn} I_n, \tag{1}$$

where: Z_{mn} — mutual impedance between two arbitrary, nth and mth, surrounding metal installations (circuits).

It is well known that distribution substations are located in areas occupied by many underground metal installations, acting as perfect grounding electrodes [20]. Thus, relationships between the relevant parameters from the equivalent circuit of Fig. 2 is such that grounding impedances Z_A and Z_B can be neglected ($Z_A \approx 0$ and $Z_B \approx 0$). Because of that, the fault currents appearing in the cable line sheaths are a consequence solely of the inductive influence of the ground fault current in the phase conductor [13]. This is in accordance with the formerly mentioned reduction factor definition. Also, for further considerations it is necessary to mention that the current directions shown in Fig. 2 are taken arbitrarily.

On the basis of the equivalent circuit presented in Fig. 2, it is possible to write the system of $(N+1)$ equations and, for the known the values of U_a and all self- and mutual impedances, determine each of the presented currents. Unfortunately, because of the previously mentioned practical difficulties and limitations, the parameters of the surrounding metal installations necessary for determination of these impedances should be treated as unknown quantities. Thus, for solving the problem of determining the current circulating through the earth, I_e, and reduction factor of the considered line, a completely new approach is necessary.

The problem is solved in [14] by measuring currents I_0 and I_1 (Fig. 2) and by substituting all surrounding metal installations by one equivalent conductor, imagined as a cylinder placed around and along the entire feeding line. Here, for the sake of simplifying the necessary calculation procedure, it will be assumed that this conductor also involves two metal sheaths of the remaining two single-core cables, through which the ground fault current does not circulate. Under this assumption, the considered cable line is transformed into the physical model whose cross-section is shown in Fig. 3.

For the equivalent conductor defined in such manner, the corresponding equivalent circuit of the entire cable line obtains the appearance as shown in Fig. 4.

The used notation has the following meaning:

U_{0C}, U_{1C} — voltages that current I_C induces in the phase conductor and its metal sheath,

U_{C0}, U_{C1} — voltages that currents I_t and I_1 induce in the equivalent conductor.

The relevant parameters of the assumed equivalent conductor will be determined under condition that currents I_t and I_1 in Fig. 3 remain unchanged. By using the equivalent circuit presented in Fig. 4, this

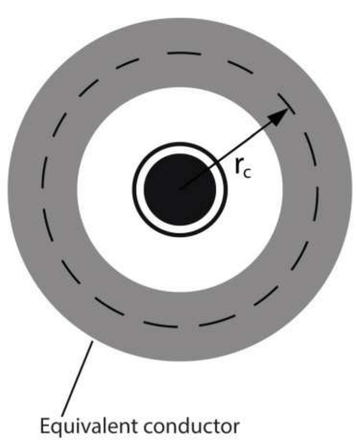

Figure 3. Cross section of the introduced line model.

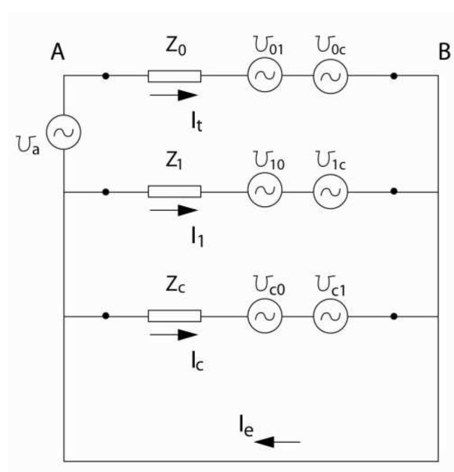

Figure 4. Equivalent circuit of the introduced line model.

condition can be expressed by the following system of equations

$$\begin{aligned} &1.\ Z_{01}I_0 + Z_1I_1 + Z_{1C}I_C = 0 \\ &2.\ Z_{0C}I_0 + Z_{1C}I_1 + Z_CI_C = 0 \end{aligned} \tag{2}$$

where Z_C — self-impedance of the equivalent conductor, and Z_{1C} — mutual impedance between the equivalent conductor and the remaining cable metal sheath.

Impedances Z_1 and Z_{01} are determined, according to e.g., [13], by the following expressions:

$$Z_1 = R'_S + \omega\frac{\mu_0}{8} + j\omega\frac{\mu_0}{2\pi}\ln\frac{\delta}{r_S}; \quad \Omega/\text{km} \tag{3}$$

$$Z_{01} = \omega\frac{\mu_0}{8} + j\omega\frac{\mu_0}{2\pi}\ln\frac{\delta}{r_S}; \quad \Omega/\text{km}. \tag{4}$$

The equivalent earth penetration depth δ is determined by

$$\delta = 658\sqrt{\frac{\rho}{f}}; \quad \text{m}, \tag{5}$$

where ρ — equivalent soil resistivity in Ωm, and f — network frequency, 50 or 60 Hz.

Here, it should be mentioned that these expressions are based on Carson's theory of the current return path through the earth. They have been derived under the assumptions that the power line was laid in a homogeneous soil of a resistivity equal to the equivalent resistivity of the normally heterogeneous (multilayer, with each layer having different resistivity) soil.

For the adopted physical appearance of the equivalent conductor, the impedances Z_C, Z_{0C}, and Z_{1C} are determined by

$$Z_C = R'_C + \omega\frac{\mu_0}{8} + j\omega\frac{\mu_0}{2\pi}\ln\frac{\delta}{r_C}; \quad \Omega/\text{km} \tag{6}$$

$$Z_{0C} = Z_{1C} = \omega\frac{\mu_0}{8} + j\omega\frac{\mu_0}{2\pi}\ln\frac{\delta}{r_C}; \quad \Omega/\text{km} \tag{7}$$

where r_c — medium radius of the cylinder representing the equivalent conductor, and R'_C — per unit length resistance of the equivalent conductor, Ω/km.

Since currents I_0 and I_1 represent known quantities, obtained by measurements, the condition given by (1) can be modified as follows

$$\frac{Z_{0C}Z_{1C} - Z_CZ_{01}}{Z_CZ_1 - Z_{1C}^2} = \frac{I_1}{I_t}. \tag{8}$$

In the given expression the only unknown quantities, according to (3), (4), (6), and (7), are R'_C and r_c. Since (8) gives the relationship between complex quantities, it can be presented as the following system of two equations

$$\begin{aligned} \text{Re}\left\{(Z_{0C}Z_{1C} - Z_C\,Z_{01})\ I_t\right\} &= \text{Re}\left\{\left(Z_CZ_1 - Z_{1C}^2\right)\ I_1\right\} \\ \text{Im}\left\{(Z_{0C}Z_{1C} - Z_C\,Z_{01})\ I_t\right\} &= \text{Im}\left\{\left(Z_CZ_1 - Z_{1C}^2\right)\ I_1\right\} \end{aligned} \tag{9}$$

After determining the relevant parameters of the equivalent conductor (R'_C and r_C), relations (8) and (9) can be used for obtaining: Z_{1C}, Z_{0C} and Z_{1C}, as well as: I_c and I_e (Fig. 4). Then, in accordance with the equivalent circuit in Fig. 4 and the reduction factor definition, the actual feeding line reduction factor is

$$r = \frac{I_e}{I_t} = 1 - \frac{(Z_C - Z_{1C})\,Z_{01} + (Z_1 - Z_{1C})\,Z_{0C}}{Z_1Z_C - Z_{1C}^2} \tag{10}$$

or, according to (6) and (7), in somewhat more compact form

$$r = 1 - \frac{R'_CZ_{01} + (Z_1 - Z_{1C})\,Z_{0C}}{Z_1Z_C - Z_{1C}^2} \tag{11}$$

In the case of the line consisting of three single-core cables, the reactive parts of impedances Z_1 and Z_{1C} are practically equal ($X_1 \approx X_{1C}$) and because of that, instead of (11), the following approximation can be used

$$r \approx 1 - \frac{R'_C Z_{01} + R_1 Z_{0C}}{Z_1 Z_C - Z_{1C}^2} \tag{12}$$

The calculation procedure performed by using (11), or (12), is obviously somewhat simpler than the one described in [13, 14].

The same procedure can be used for evaluation of the current induced by an existing HV distribution line in the planed neighboring (e.g., in the same pavement, or in the same street) insulated metal pipeline or for evaluating the electromagnetic compatibility problems. For this purpose, it is necessary to represent all surrounding metal installations, including all line neutral conductors, by only one equivalent neutral conductor which is cylindrical in form and placed around the faulty phase conductor along the entire HV line. On the basis of the equivalent circuit of Fig. 4, the relevant parameters of this equivalent conductor can be determined by

$$R'_{eq} = \mathrm{Re}\left\{Z_1 Z_C - Z_{1C}^2\right\} \tag{13}$$

$$r_{eq} = \frac{\delta}{e^{2\pi X_{eq}/\omega\mu_0}} \tag{14}$$

where R'_{eq} and X'_{eq} — real and imaginary parts of the self-impedance of the new equivalent conductor, and r_{eq} — radius of the equivalent neutral conductor.

When the relevant parameters of the equivalent conductor are known, the solution of the problem of the inductive influence on one of the surrounding metal installations reduces to the extremely simple case. Bearing in mind the physical appearance and position of the adopted equivalent neutral conductor, the mutual impedance between this conductor and the planed nearby pipeline is the same as the mutual impedance between the phase conductor and this pipeline. Thus, the whole problem reduces to the extremely simplest case which is represented by the equivalent circuit of Fig. 5.

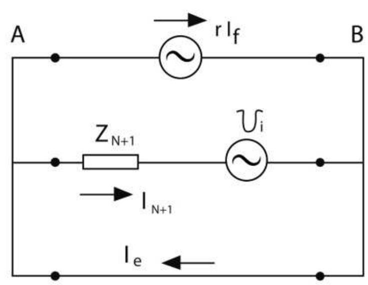

Figure 5. Inductive influence on one of the surrounding installations.

The used notation has the following meaning:

rI_f — ideal current source,

I_{N+1} — current which will be induced in the planed pipeline,

$Z_{(N+1)}$ — self-impedance of the planed pipeline, and

$Z_{(N+1)0}$ — mutual impedance between the nearest (critical case) phase conductor and the planed pipeline.

On the basis of the equivalent circuit given in Fig. 5, the voltage, which will be induced along (per unit length) the planed pipeline, U'_i, can be determined by

$$U'_i = -rZ_{(N+1)0} I_f; \quad \mathrm{V/km} \tag{15}$$

When the relevant parameters of the equivalent neutral conductor are determined, the actual reduction factor can be determined by using, instead of (11), the following well-known and simpler analytical expression

$$r = \frac{R'_{eq}}{R'_{eq} + \omega \frac{\mu_0}{8} + j \frac{\omega \mu_0}{2\pi} \ln \frac{\delta}{r_{eq}}} \tag{16}$$

Also, mutual impedance between the nearest phase conductor and the planed pipeline which will be laid along the same street(s) with an existing HV distribution line is

$$Z_{(N+1)0} = \omega \frac{\mu_0}{8} + j\omega \frac{\mu_0}{2\pi} \ln \frac{\delta}{D}; \quad \Omega/\text{km} \tag{17}$$

where D — distance between the nearest phase conductor and the planed pipeline.

Since the ground fault current is a quantity known from a separate analysis, for determination of U'_i it is, according to (15), necessary to determine only the mutual impedance, $Z_{(N+1)0}$. As it is well-known, it can be made on the basis of the foreseen mutual distance (D) of the planed pipeline with respect to the nearest phase conductor of the considered HV line. Since, by the using developed method, the currents induced in any of the surrounding metal installations can be determined, from the mathematical point of view the following is interesting to note: the developed method enables solving the system of equations, even in the case when the number of unknown quantities (N) is also unknown.

As it can be seen, application of the presented method is possible only to an already existing power line. However, data about the actual value of the reduction factor of a distribution line, or about ground fault current distribution in a supplied substation, are usually necessary at the design stage. In that case, the problem can be solved on the basis of the fact that, according to the equivalent circuit of Fig. 2, the apparent self-impedance of each of the line conductors includes the inductive influence of all surrounding metal installations. It means that for appreciating this influence an already constructed line is not necessary. Instead, it is sufficient to use one single-core cable. It would be used for a provisory cable line laid on the surface of the soil along the foreseen path of the planed line. It is the best if for this purpose to use an LV single-core cable (with a metal sheath), sufficiently flexible for different practically possible urban conditions. Also, for simulating the ground fault conditions and obtaining the corresponding currents (I_0 and I_1), an auxiliary voltage source is necessary. For the purpose of grounding electrode of a supplied substation one can be use steel reinforcement in the foundation of one of the existing buildings nearest to the future supplied substation.

Since the surrounding metal installations already exist, and will exist in the unchanged spatial positions, the electrical circuits formed by using the provisory cable line can also be represented by the equivalent circuit of Fig. 2. The only difference stems from the fact that in this case there is only one neutral line conductor. By appreciating this change, the voltages and current in the provisory cable line, according to the equivalent circuit of Fig. 2, are connected by the following equation

$$U_a = Z_0 I_0 + Z_{01} I_1 + \sum_{n=4}^{n=N} Z_{0n} I_n. \tag{18}$$

According to (17), values of the currents I_0 and I_1 reflect cumulative influence of all, known and unknown surrounding metal installations. Thus, when the ratio between currents I_0 and I_1 is determined by the corresponding measurements, the influence of all surrounding metal installations [15], including line neutral conductors, can be substituted by only one equivalent neutral conductor. Then, the actual reduction factor of the HV distribution line can be determined by using the calculation procedure presented in [14, 15].

Since the metal installations in urban areas are mainly under the soil surface, the measured influence of the surrounding metal installations will be slightly smaller in the case of a planned underground line, or slightly greater in the case of a planned overhead line. Since the overhead line conductors are placed at a greater distance from the surrounding metal installations, the value of the radius of the cylinder representing the surrounding metal installations in this case of these lines should by enlarged by the average pole height [16].

According to the presented analytical procedure, the developed method enables determination of the reduction factor of any of the existing or planned distribution lines. It enables taking into account all relevant factors and parameters, including even those whose influence is very small. It means that by applying this method each practical situation, including extremely complex ones, becomes solvable.

Some inaccuracy can appear only as a consequence of the inductive influence of the nearby power distribution lines. This influence can be efficiently avoided by using the test current of somewhat higher frequency which can easily be discriminated from the omnipresent power frequency (e.g., [10, 15]). The introduced error is small and gives the final results that are slightly on the safe side.

Although there are several methods of measurement of soil resistivity (e.g., [1]), no one of them is applicable in urban conditions (e.g., [15]). The reason stems from the fact that the surfaces of urban areas are already occupied by buildings, streets, pavements, and many other permanently constructed objects, while under the ground surface many known and unknown metal installations are already present. Thus, one is forced to adopt an approximate value of the equivalent soil resistivity, based on the main geological characteristics of the relevant area, and use it in the calculative part of the developed method. Here, the favorable circumstance is that the self- and mutual impedances are, according to the given equations, only slightly dependent on the equivalent soil resistivity and a more accurate data about this parameter do not bear any practical significance. It is sufficient to know that, within the range of actually possible values, the lowest one should be preferred because it gives final result which is slightly on the safe side. Thus, it can be said that accuracy of the developed method depends practically only on the accuracy of the measurements of the currents I_0 and I_1.

4. THE EXPERIMENTAL INVESTIGATIONS

The experimental investigations of the influence of metal installations, typical of urban areas, on value of the feeding line reduction factor are performed with a cable line that supplies, in series, two substations of the 110 kV distribution network in Belgrade, Serbia [14]. Length of the line to the closer of the two supplied substations, measured from the supply substation, is 2320 m, while the feeding line length to the more distant substation is 6590 m. The line is realized by XHLP cables having mutually identical design parameters and laid in a triangular formation over the entire line length. The cross-bounding technique necessary for reduction of circulating currents was not applied.

In the areas through which the line is passing the specific soil resistivity is estimated on the basis of the main geological characteristics of the relevant area, i.e., the only possible way for doing this for urban areas. The roughly estimated equivalent soil resistivity of the entire area is within the range from 30 to 50 Ωm. The line section between the supply and the transit (nearer) substation passes through the area with a lower degree of urbanization compared with the rest of the line. The phase conductors are made of aluminum of a cross-section of 1000 mm^2, while the metal sheaths are made of copper strings of a total cross-section of 95 mm^2, and of medium diameter of 91 mm. The described line is used to obtain the experimental results for two different feeding cable lines, one 2320 m and the other 6590 m long.

At first, by simulating single-phase ground fault in the supplied substation and by disconnecting all three cable sheaths from the grounding electrode at one of the line ends, the following values for the phase conductor self-impedances were obtained

- $Z_{pha} = (0.1819 + j1.0243)\,\Omega$, for the line 2320 m, and
- $Z_{pha} = (0.5167 + j2.6260)\,\Omega$, for the line 6590 m.

By using the analytical expressions for this impedance (e.g., [14]) the corresponding values of the parameters δ and ρ are:

- $\delta_a = 20.9$ m, or $\rho_a = 0.052\,\Omega$m, for the shorter line and
- $\delta_a = 10.88$ m, or $\rho_a = 0.0137\,\Omega$m, for the longer line.

Since the considered cable lines pass through areas covered by many others metal installations that affect the obtained results of the performed measurements (Fig. 2). Thus, the obtained values can be treated only as apparent, and because of that they are denoted as: Z_{pha}, δ_a and ρ_a.

The aim of the second set of measurements was determination of the reduction factor of the considered lines by using at that moment the only known method which is based only on the measurements of the currents induced in the cable sheaths [14]. For this purpose all three cable sheaths were grounded at both line ends and the following values of the line reduction factor were obtained

- $r = 0.0473 - j0.1565$, for the shorter line, and

- $r = 0.0637 - j0.1724$, for the longer line.

The obvious difference between the two presented values can be explained by the fact that the shorter line passes through an area of a lower degree of urbanization, i.e., of a lower number of surrounding metal installations.

However, on the basis of the equivalent circuit of Fig. 2, it is not difficult to see that the presented results do not involve the currents induced in the surrounding metal installations. Also, currents measured in the cable sheaths are affected by the currents induced in the surrounding metal installations. Because of this, the line reduction factor obtained by these measurements is several time higher than the actual one. This will be shown by the method presented here and the quantitative analysis presented in the following section.

Based on the experimental results, the following facts can be noted. The apparent equivalent soil resistivity obtained by the measurements is drastically lower compared to the actual value (approximately valued between 30 and 50 Ωm). The corresponding values of the reduction factor are by 52.1% and 69.6% higher than the value obtained by using the approximately estimated actual equivalent soil resistivity, $r(\rho = 30\,\Omega\text{m}) = 0.0204 - j0.1037$ and by using the analytical expressions obtained under the assumptions that the other metal installations do not exist in the surrounding earth which is semi-infinite and homogenous [2, 13].

In accordance with the previous considerations the presence of other metal installations, typical for urban areas, reduces not only the current flowing through the earth, but also the current circulating through the cable metal sheath(s). Since the line reduction factor is defined as the ratio I_e/I_f (Fig. 2), for obtaining the actual value of the reduction factor, presence of the surrounding metal installations has to be taken into account. However, determination of current I_e only by experimental measurements is not practically possible.

5. THE QUANTITATIVE ANALYSIS

By using the previously described method, one obtains that the actual reduction factor taking into account the influence of the surrounding metal installations in the cases of the experimentally considered lines is:

- $r = -0.0267 - j0.0245$, or $|r| \approx 0.036$, for the shorter, and
- $r = -0.0225 - j0.0170$, or $|r| \approx 0.029$, for the longer line.

It can be seen that its effective values are by 65.9% and 72.6% lower than the value obtained by using the analytical expression [2, 13] which cannot take into account the influence of the surrounding metal installations ($|r| \approx 0.105$).

If it is assumed that the cables in the considered cases are laid in a flat formation, at a distance of $d = 0.5$ m, one obtains

$r = -0.0275 - j0.0297$, or $|r| = 0.0405$ for the shorter and

$r = -0.0232 - j0.0202$, or $|r| = 0.0308$, for longer line.

The differences are still greater in comparison with the reduction factor values obtained only by measurements of the currents in the cable sheaths; the actual values are lower by: 78.0% and 84.2%, respectively. Obviously, disregarding the influence of metal installations surrounding a feeding line, as well as determining the reduction factor only by measuring currents through the cable sheaths gives results which are excessively inaccurate.

Bearing in mind that this reduction of the line reduction factor also means reduction by the same ratio of all potentials appearing in the grounding systems of the supplied substations, one can conclude that the results of this analysis throw a completely new light at the grounding problem of the supplied substations. Also, having in mind similarity of urban conditions all over the world and that the experimental measurements were performed in the areas which can be treated as average from the standpoint of the achieved degree of urbanization, this conclusion can be treated as generally valid for the safety conditions of the distribution substations located in urban areas.

Certainly, greater economical effects can be expected in cases where, because of a high soil resistivity and/or a high short-circuit current levels, thus special measures (e.g., bare copper conductor laid in the same trench as the cable feeding line, counterpoises, etc.) were in the past considered necessary [8]. Moreover, one can expect elimination of the strict requirement for the application of expensive MV cables acting as grounding conductors (cables with an uncovered sheath), as was the case with the MV distribution network of Beograd [14, 15]. The only inconvenience arises from the fact that the actual ground fault current distribution depends on the concrete metal installations laid in the area through which the feeding line passes. It practically means that for obtaining actual ground fault current distribution, each distribution line passing through urban and/or suburban areas should be considered individually.

Now, it will be assumed that the ground fault current passing through the considered lines is 20 kA and that the planned metal pipeline will be laid in the same pavement at the distance equal 1 m from the nearest phase conductor. On the basis of (15) and the reduction factor determined by the existing analytical expression [2], one obtains that the voltage induced in the planned pipeline will be 822.5 V/km. However, if one takes into account the influence of the surrounding metal installations, this value is significantly smaller, i.e., 282 V/km for the shorter and 227.2 V/km for the longer line. If one assumes that the distance between HV line and the planned pipeline is 20 m, the corresponding induced voltages would be: 731 V/km, 250.6 V/km and 201.9 V/km, respectively. The presented results show that the influence of the surrounding metal installations should not be ignored when one evaluates the inductive influence of the HV power lines passing through urban areas.

Since the cable lines are, almost without any exception, applied in urban areas and since the effects of the surrounding metal installations are considerable, the presented method should be used as a foundation for the revision of the current version of the corresponding technical standard [2].

6. CONCLUSIONS

The presented method enables taking into account the favorable influence of urban metal installations surrounding HV distribution lines on the ground fault current distribution in the supplied substation(s), located in urban and/or suburban areas, or where many relevant data are uncertain or completely unknown. Application of the proposed method requires performing on-the-site measurements of the test currents in one of the phase conductors and in one of the neutral conductors of the considered power line. The necessary calculations can be implemented for any practical situation by using handheld calculators.

Also, application of the presented method enables determination of the induced current and voltage due to electromagnetic fields of energized lines in each of the surrounding metal installations seen separately.

Bering in mind the obvious simplicity and efficiency of the presented method, it can be used as a foundation for the revision of the existing technical standards in this field.

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