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DETERMINATION OF ACTUAL REDUCTION FACTOR OF HV AND MV CABLE LINES PASSING THROUGH URBAN AND SUBURBAN AREAS

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Abstract: *The paper presents the method for determination of ground fault current distribution in the cases when feeding cable lines are passing through urban and/or suburban areas, or when many relevant data are uncertain, or completely unknown. The problem appears as a consequence of the fact that many of surrounding urban installations are situated under the surface of the ground and cannot be visually determined or verified. On the basis of on site measurements, the developed method enables compensation of all deficiencies of the relevant data about metal installations involved with the fluctuating magnet field appearing along and around of a power line during an unbalanced fault. The presented analytical procedure is based on the fact that certain measurable quantities cumulatively involve the inductive effects of all, known and unknown surrounding metal installations. The performed quantitative analysis points on at the significance of taking into account the existence of surrounding metal installations.*

Key words: *substation, grounding system, ground fault current, inductive influence*

1. INTRODUCTION

The fault current during an earth fault in a power network has at least two alternative paths for returning to the source which feeds the fault. Because of that, each ground fault current has at least two fractions. One of them is injected into surrounding earth through the grounding system of a supplied substation, while the other is returning 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 the safety conditions on the grounding system of a supplied substation, while other causes the thermal stress on the neutral conductor(s) of the feeding line. Thus, the correct estimation of the ground fault distribution is of prime importance for correct designing of the grounding system of a supplied substation and correct selection of the feeding line neutral conductor(s).

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With the aim of defining the influence of available return paths on the ground fault current distribution, a special parameter of feeding line is introduced in 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. By this, it is assumed that the grounding impedances at both line ends are negligible (e.g. [2]). Under such assumption the fault current(s) in the line 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.

With the aim of solving the problem of determination of ground fault current distribution, an extensive and continuous research work has been done in the last at least five decades.

The firstly developed methods for solving this problem relate to the case when the feeding line is constructed as an overhead line, e.g. [3]-[5]. Somewhat later, the papers considering this problem in special cases, i.e. when a feeding line appears as a longitudinal combination of one cable and one overhead section, have been published, e.g. [6], [7]. Also, several methods have been developed for solving the problem in cases where, because if high local soil resistivity and/or a high short-circuit level, special measurements (e.g. bare copper conductor laid in the same trench as the cable returning line, counterpoises, etc.) in the aim of reducing the part of ground fault current returning exclusively through the earth are considered indispensable [8]-[10]. Then, the papers [11], [12] present the method developed for determination of the ground fault current distribution when a feeding cable line is constructed of three single-core cables. The method enables taking into account the participation of all three metal sheaths on ground fault current distribution for the fault at any place along the line.

The common characteristic of the mentioned methods is that the value of the reductions factor depends only on design/constructive characteristics of a feeding line and on characteristics of the surrounding earth as a conductive medium. Thus, none of the mentioned methods enables obtaining the solution of this problem when it appears in urban and suburban conditions, when many other metal installations participate in the ground fault current returning to the power system. In such surroundings each power-cable line represents a very complex electrical circuit with many conductively and inductively coupled elements having uncertain or completely unknown parameters.

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

The investigation results presented in [14], [15] show that part 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 be seen in realistic frameworks and solved in each concrete case without any redundant expenditure.

The developed method simultaneously gives possibility of solving another problem of the current engineering practice that has also not been solved in the past. This is the problem of determination of the feeding line series impedance without ignoring the fact that the surrounding metal installations are attendant. Namely, on the basis of the imagined physical appearance of the introduced equivalent conductor, it is not difficult to see that this conductor acts as an additional neutral conductor of each distribution line passing through urban and suburban areas and, in accordance with this, improves its transfer characteristics [16].

This paper presents the theoretical foundations of the mentioned method in the more transparent and complete manner and introduces certain improvement in the development procedure of the calculative part of the method. This improvement enables a more direct and easier determination of the actual ground fault current part dissipated through the grounding system of the supplied substation into the surrounding earth and returning to the power system only through the earth.

2. Problem Description

The 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.) close to HV and MV distribution lines. Space dispositions of all of these installations, determined mainly by dispositions of city streets, and small mutual distances result in an inductive and, in the vicinity of substations, conductive coupling of different network types.

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

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

One of the main parameters for estimation of these mutual interactions, soil resistivity of the surrounding area, can not be determined exactly. Although there are several methods to measure the soil resistivity [1], no one of them can be practically applied in urban conditions. The reason stems from the fact that the surface of urban areas are already covered/occupied by buildings, streets, pavements and many other permanently constructed objects; while under the ground surface many known and unknown metal installations already exist.

Many urban metal installations of different basic functions are usually situated in a relatively small 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 concrete 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 notified and 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 substations [17]. 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 low-voltage (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 the conductive connections with the metal installations laid along the same street(s) as the feeding line. Thus, it is not difficult to notice that in the case of unbalanced operating conditions two, essentially different, currents flow out of the power system. One of them is dissipated into the surrounding earth through the grounding system of the supplied substation, while the other is induced in the metal installations surrounding the feeding line. As an illustration, these two, mutually separated fault currents, when a ground fault occurs in the substation supplied by a three-phase line, are presented in Fig. 1.

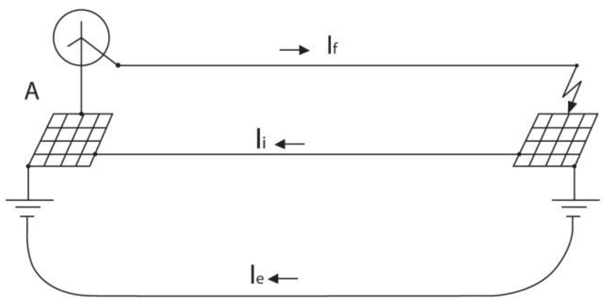

Fig. 1 Current fractions passing through the elements of the grounding systems

The used notation has the following meaning:
A – supply substation,
F – ground fault place (supplied substation),
I_f – ground fault current,
I_i – ground fault current component induced in metal installations surrounding the feeding line, and
I_e – ground fault current component injected into the earth.

Both of the presented ground fault current fractions leave power system through the elements of the grounding system of the supplied substation, F. The current, I_e, is injected into the earth, while the other, I_i, circulates only through the surrounding metal installations that are foreseen for some others purposes. Because of that all potentially dangerous and harmful influences of power - cable lines and supplied substations on their environment emanate from these two ground fault current components. Accordingly, determination of these two currents is of prime importance for estimating the safety conditions within, and in the vicinity, of a supplied substation and inductive influence of a feeding line on the neighboring parallel circuits (pipeline, telecommunication line, etc).

Since the process of splitting to these two 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 an electrical circuit, while all together these paths form a large number of conductively and inductively coupled circuits. Since these circuits can be represented by the corresponding system of equations and since the analytical expressions necessary for the self and mutual impedances of metal conductors are known [2], it can be said that the considered problem has been in principle solvable long ago. However, it is not possible because of many practical difficulties and limitations in collecting for calculations necessary data. Thus, the problem can be defined as follows: How to find the method enabling the compensation of the lack of huge number of relevant data?

3. Experimental Investigation

The experimental investigations of the influence of metal installations, typical of urban areas, on value of the feeding line reduction factor are performed on 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, 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 involved area, the only possible way for doing this in 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 metallic sheaths are made of copper strings of a total cross-section of 95 mm^2 and a medium diameter of 91 mm. The main elements of the grounding system in both supplied substations are the station building foundation and the 44 MV outgoing cable lines performed by cables with uncovered metal sheaths. The grounding impedances of the supply substation and of both of the supplied substations, determined by standard measurements, were found to be between 0.02 and 0.03 Ω. Since these impedances are very small compared to the other parameters influencing measured values of the reduction factor, they are completely disregarded.

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. This was achieved in the following manner. The longer line is obtained as a continuous cable line along its entire length by disconnecting its metal sheaths from the grounding electrode of the transit substation. The necessary measurements are performed by using the test circuit schematically represented in Fig. 2.

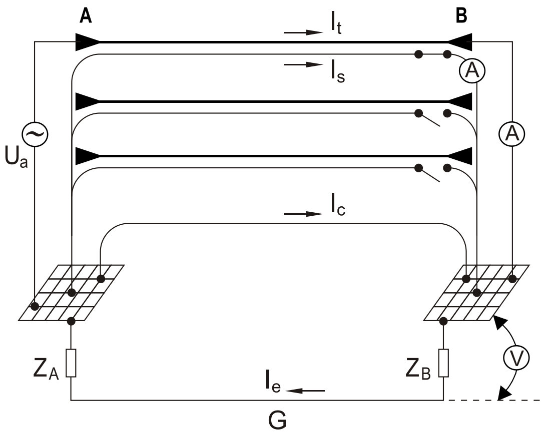

Fig. 2 Measurement circuit

The used notation has the following meaning:

A and B – substations connected through the tested cable line,
U_a – auxiliary voltage source,
I_t – test current,
I_s – current induced in the cable sheath,
I_c – total current induced in the surrounding metal installations,
I_e – current injected into the earth through the grounding system of substation B,
$Z_A\,(Z_B)$ – impedance of the grounding system of substation A(B), and
G – remote ground.

The influence of the surrounding metal installations has been observed by measuring value of the self - impedance of one of the line phase conductors and by using the known analytical expressions for this impedance that is, according to e.g. [2], given by

$$Z'_{ph} = R'_{ph} + \omega\frac{\mu_0}{8} + j\omega\frac{\mu_0}{2\pi}\left(\frac{\mu_r}{4} + \ln\frac{\delta}{r_{ph}}\right) \quad ; \quad \Omega/\text{km}, \tag{1}$$

where
R'_{ph} – phase conductor resistance per unit length, Ω/km,
r_{ph} – outer radius of the phase conductor, m,
ω – angular frequency $\omega = 2\pi f$,
μ_0 – magnetic permeability of vacuum, $4\pi\cdot10^{-7}$ Vs/Am, and
μ_r – relative magnetic permeability.
(Prime (') denotes values per unit length).

The equivalent earth penetration depth δ is determined by the following expression

$$\delta = 658\sqrt{\frac{\rho}{f}} \quad ; \quad \text{m}, \tag{2}$$

where
ρ – equivalent soil resistivity along the cable line in Ωm, and
f – test circuit frequency.

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 is 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 and that there are no other metal installations in the vicinity of the line. However, these assumptions do not correspond to the described actual situation.

Since the considered cable lines pass through areas covered by a spontaneously formed network of different underground metal installations, the measured quantities are affected by the conductive and inductive couplings of all, known and unknown, surrounding metal installations. Thus, measurements can give only an apparent value of the self impedance of the line phase conductor.

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 (Fig. 2), the following values for the apparent phase conductor self-impedance were obtained

– Z_{pha} = (0.1819 + j1.0243) Ω, for the line 2320 m, and

– Z_{pha} = (0.5167 + j2.6260) Ω, for the line 6590 m.

The values of the line reduction factor obtained only on the bases of the measured values of the currents appearing in the cable sheaths were the following

– r = 0.0473 – j 0.1565, for the shorter line, and

– r = 0.0637 – j 0.1724, for the longer line.

When the apparent values of impedance Z'_{pha} are determined, the only unknown parameters in the given expressions, (1) and (2), ρ and δ can be obtained by using these equations. However, these parameters in the considered cases involve, besides local earth characteristics, the constructive characteristics and mutual space disposition of all others available return paths. According to this, they should be defined in somewhat different way. A new definition of the parameter ρ is that it represents the apparent equivalent soil resistivity, because it involves the conductive and inductive influences of all return paths, while the parameter δ is the equivalent penetration depth all return paths because it involves the conductive and inductive influences of all return paths. Thus, the new notation which expresses this new meaning is ρ_α and δ_a.

The corresponding values of the newly defined parameters are:

– δ_a = 20.9 m, or ρ_a = 0.052 Ωm, for the shorter line and

– δ_a = 10.88 m, or ρ_a = 0.0137 Ωm, for the longer line.

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

Since the design data concerning the tested lines, as well as the newly defined parameters ρ_α or δ_a are known, the analytical expression, for the reduction factor in the case of single-core cables laid in a triangular formation, can be tested. This expression has, according to [13], the following mathematical form

$$r = \frac{R'_S}{R'_S + 3\omega\frac{\mu_0}{8} + j3\omega\frac{\mu_0}{2\pi}\ln\frac{\delta_a}{\sqrt[3]{r_S d^2}}} \tag{3}$$

where

R'_S – metal sheath resistance per unit length, Ω/km,

d – distance between two adjacent cables (or, diameter of the single-core cable) in the case of triangular formation, and

r_S – medium radius of the cable sheath.

By applying the above expression to the considered cable lines one obtains:

- r = 0.0471 – j0.1537, for the shorter and
- r = 0.0589 – j0.1693, for the longer line.

It can be seen that the results obtained by the applied expression and the results obtained by the measurements are in good agreement, practically identical. In this way the experimental proof has been obtained for the accuracy of the given analytical expression, but under the unreal assumption that the surrounding metal installations do not exist.

Based on the experimental results, the following facts can be still noted. The apparent equivalent soil resistivity obtained in this way is drastically lower compared to the realistic soil resistivity (between 30 and 50 Ωm). The corresponding values of the reduction factor are by 52,1% and 69.6 % higher than the value obtained with the approximately estimated equivalent specific soil resistivity, $r(\rho = 30\ \Omega\text{m}) = 0.0204 - j0.1037$. This can be explained by the fact that the presence of the nearby underground metal installations reduces not only of the fault current flowing through the earth, but also the currents flowing through the cable line sheaths.

For obtaining a more complete insight into the influence of metal installations surrounding a feeding line, currents through the cable sheaths were also experimentally investigated. At first, a ground fault current distribution was observed when only the sheath of the cable with the ground fault current was connected to both grounding electrodes at the line ends. Then another situation was considered, i.e. when one more cable sheath was connected to both of the grounding electrodes at the line ends. Finally, normal operating conditions have been observed, i.e. when all three metal sheaths were grounded at the line ends.

The measurement results show that the successive increase of the number of grounded metal sheaths (Fig. 2) reduces not only the current flowing through the earth, but also the relative participation of each of the already connected sheaths in reducing the fault current through the earth. These relative reductions in the case of the sheath of the cable with simulated ground fault are from 60.66% to 46.31% and from 46.31% to 37.49%, respectively. These results are helpful for understanding the influence of the surrounding metal installations.

Since the reduction factor is defined as the ratio I_e/I_f, for obtaining the actual value of the reduction factor the presence of the surrounding metal installations has to be taken into account.

4. METHOD DEVELOPMENT

On the basis of the former analysis, 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 line phase conductors are excluded, is equal to the number of the line neutral conductors enlarged by the number of surrounding metal installations.

If again the cable line presented in Fig. 2 is considered, but now, with all metal sheaths grounded at both line ends, and if it is assumed that the total number of surrounding metal installations, including the neutral conductor, is equal to an arbitrary number N, then this line can be represented by the equivalent circuit shown in Fig. 3.

An arbitrary current in Fig. 3, I_n, induces in an also arbitrary (mth) current circuit, voltage, U_{mn}, determined by

$$U_{mn} = Z_{mn} I_n \tag{4}$$

where

Z_{mn}– mutual impedance between two arbitrary (nth and mth) surrounding metal installations (circuits), Fig. 3.

It is well known that distribution substations are located in areas occupied by many underground metal installations, acting as perfect grounding electrodes [17]. Thus, 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 metal sheaths are a consequence solely of the inductive influence of the ground fault current appearing in the faulted phase conductor [15]. 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. 3 are taken arbitrarily.

On the basis of the equivalent circuit presented in Fig. 3 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 in the given equivalent circuit 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_t and I_1 (Fig. 2) and by substituting all surrounding metal installations by one equivalent conductor that is 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

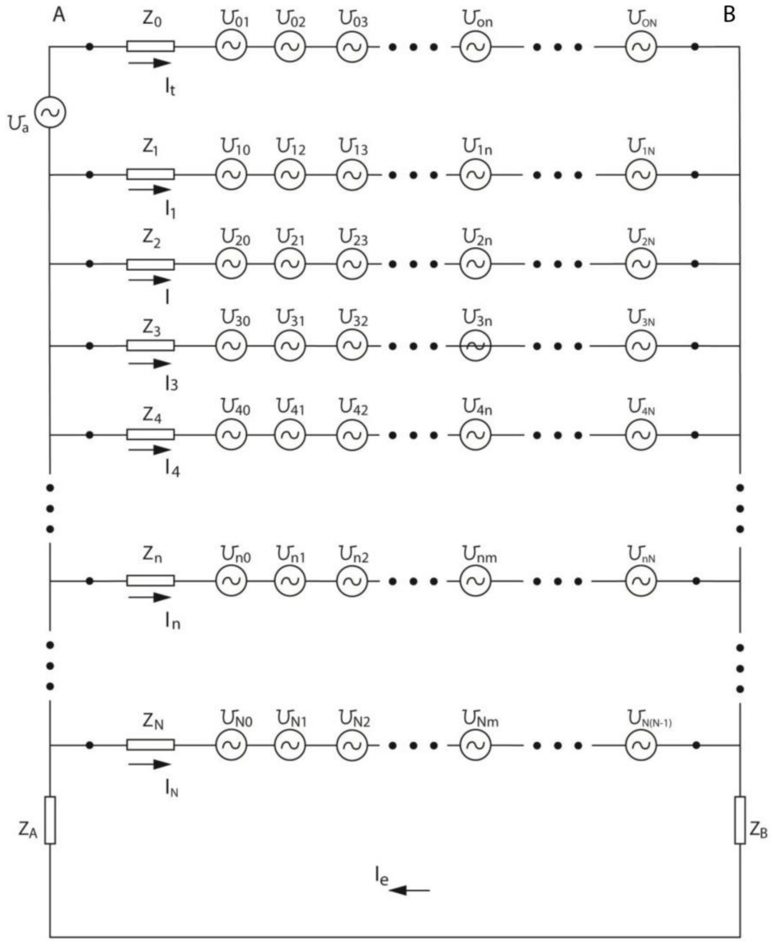

Fig. 3 Complete line equivalent circuit

The used notation has the following meaning

U_a – auxiliary voltage source,

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

I_t – test current through the phase conductor of the considered line,

I_1,– current through the sheath of the cable with the current I_t,

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

I_4, I_5, I_6 , … ,I_n, …, I_N - currents induced in the individual surrounding metal installations

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

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

two sheaths of the remaining single-core cables through which the ground fault current do not circulate. Under such assumption the considered cable line is transformed into the physical model whose cross-section can be represented as shown in Fig. 4.

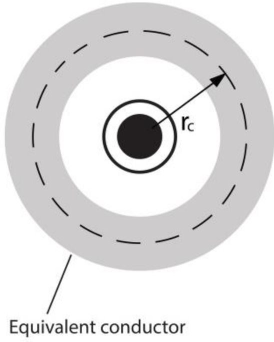

Fig. 4 Cross section of the introduced line model

For the equivalent conductor imagined in such manner, the corresponding equivalent circuit of the entire cable line has the appearance as shown in Fig. 5.

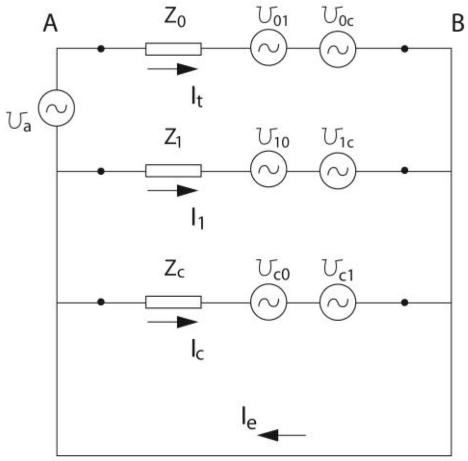

Fig. 5 Equivalent circuit of the introduced line model

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 after introducing the equivalent conductor, Figs. 4 and 5. By using the equivalent circuit presented in Fig. 5 this condition can be expressed by the following system of equations

$$\begin{aligned} &1.\ Z_{01}I_t + Z_1 I_1 + Z_{1C} I_C = 0 \\ &2.\ Z_{0C}I_t + Z_{1C}I_1 + Z_C I_C = 0 \end{aligned} \tag{5}$$

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

Impedances Z_1 and Z_{01} are determined, according to e.g. [14], by the following expressions:

$$Z_1 = R'_S + \omega\frac{\mu_0}{8} + j\omega\frac{\mu_0}{2\pi}\ln\frac{\delta}{r_S}\;;\;\;\Omega/\text{km} \tag{6}$$

$$Z_{01} = \omega\frac{\mu_0}{8} + j\omega\frac{\mu_0}{2\pi}\ln\frac{\delta}{r_S}\;;\quad\Omega/\text{km} \tag{7}$$

For the adopted physical appearance of the equivalent conductor, the analytical expressions for impedances Z_C, Z_{0C}, and Z_{1C} are

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

$$Z_{0C} = Z_{1C} = \omega\frac{\mu_0}{8} + j\omega\frac{\mu_0}{2\pi}\ln\frac{\delta}{r_C}\;;\;\;\Omega/\text{km} \tag{9}$$

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

Since currents I_t and I_1 represent the known quantities, obtained by measurements (Fig. 2), the condition given by (5) can be modified to the folowing simpler form

$$\frac{Z_{0C}Z_{1C} - Z_C Z_{01}}{Z_C Z_1 - Z_{1C}^2} = \frac{I_1}{I_t} \tag{10}$$

In the given expression the only unknown quantities, according to (6), (7), (8), and (9), are R'_C and r_c. Since (10) gives the relationship between complex quantities, it can be presented in the form of the following system of two equations

$$\begin{aligned} &\text{Re}\left\{\left(Z_{0C}Z_{1C} - Z_C Z_{01}\right)I_t\right\} = \text{Re}\left\{\left(Z_C Z_1 - Z_{1C}^2\right)I_1\right\} \\ &\text{Im}\left\{\left(Z_{0C}Z_{1C} - Z_C Z_{01}\right)I_t\right\} = \text{Im}\left\{\left(Z_C Z_1 - Z_{1C}^2\right)I_1\right\} \end{aligned} \tag{11}$$

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. Then, in accordance with the equivalent circuit in Fig. 5 and the reduction factor definition, the feeding line reduction factor is determined by

$$r = \frac{I_e}{I_t} = 1 - \frac{\left(Z_C - Z_{1C}\right)Z_{01} + \left(Z_1 - Z_{1C}\right)Z_{0C}}{Z_1 Z_C - Z_{1C}^2}\,, \tag{12}$$

or, according to (8), and (9), in somewhat more compact form

$$r = 1 - \frac{R_C' Z_{01} + (Z_1 - Z_{1C}) Z_{0C}}{Z_1 Z_C - Z_{1C}^2} \tag{13}$$

Condition defined by (5) means at the same time:

$$U_{0C} = Z_{0C} I_C = \sum_{n=2}^{N} Z_{0n} I_n \text{, and} \tag{14}$$

$$U_{1C} = Z_{1C} I_C = \sum_{n=2}^{N} Z_{1n} I_n \tag{15}$$

On the basis of (14) and (15) it is clear that the introduced equivalent conductor substitutes many known and unknown relevant parameters.

Data about actual reduction factor of a distribution line, or about actual ground fault current distribution in a supplied substation, are usually necessary before the line has been constructed. In these cases, for performing of the previously defined measurements one can utilize a provisory cable line posed on the surface of the soil along the foreseen path of the future line. This can be done by using any single-core cable suitable for this purpose in different, practically possible conditions and by using calculation procedure described here. Since the metal installations in urban areas are mainly under the soil surface, the considered inductive influence will be slightly smaller [16].

According to the developed analytical procedure, the presented method enables determination of the reduction factor of any type of cable lines and takes into account all relevant factors and parameters, including even those whose contribution is negligibly small. It means that this method enables a correct problem solution for each, including extremely complex, practical situation. 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 that can easily be discriminated from the omnipresent power frequency (e.g. [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 covered/occupied by buildings, streets, pavements, and many other permanently constructed objects; while under the ground surface many known and unknown metal installations already exist. Thus, one is forced to adopt an approximate value of equivalent soil resistivity, based on the main geological characteristics of the relevant area, and use it in the calculation 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 does not bear any practical significance. It is sufficient to know that, within the framework of actually possible values, the lowest one should be preferred because it gives final results that are slightly on the safe side.

5. Quantitative Analysis

By using the previously described method we obtain that the reduction factor taking into account the influence of the surrounding metal installations in the cases of the considered lines is:

– $r = -0.0267 - j0.0245$, or $|r| \approx 0.036$, for the shorter, and
– $r = -0.0225 - j\,0.0170$, 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 without taking into account 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 and at a distance of $d = 0.5$ m, one obtains

$r = -0.0275 - j0.0297$, or $|r| = 0.0405$ for the shorter and
$r = -0.0232 - j\,0.0202$, or $|r| = 0.0308$, for longer line.

The differences are still greater in comparison with the previously given results of measurements; the obtained values are lower in this case: 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 give results that are excessively conservative.

Bearing in mind that this also means the reduction by the same ratio of all potentials appearing on the grounding systems of the supplied substations, one can conclude that the results of this analysis throw a completely new light on the grounding problem of the supplied substations. Also, having in mind the similarity of the urban conditions all over the world, this conclusion can be treated as generally valid for the safety conditions of the distribution substations supplied by cable lines.

Certainly, greater economical effects can be expected in cases where, because of a high soil resistivity and/or a high short-circuit current level, special measurements (e.g. bare copper conductor laid in the same trench as the cable feeding line, counterpoises, etc.) were considered necessary. Besides, 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 network of Beograd. The only difficulty arises from the fact that the actual ground fault current distribution depends on the metal installations laid in the area through which the feeding line passes. It practically means that for obtaining actual ground fault current distribution, each concrete distribution line should be considered separately.

6. Conclusions

The presented method enables taking into account the favorable influence of urban metal installations surrounding HV and MV distribution cable lines on the ground fault current distribution in the supplied substation(s).

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

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