International Journal of Applied Power Engineering (IJAPE)
Vol. 12, No. 4, December 2023, pp. 451~462
ISSN: 2252-8792, DOI: 10.11591/ijape.v12.i4.pp451-462

Effective metal shields of high voltage distribution cable lines

Ljubivoj M. Popović
J. P. Elektrodistribucija-Beograd, Elektroprivreda Srbije, Beograd, Serbia

Article Info

Article history:

Received Apr 5, 2023
Revised May 21, 2023
Accepted May 25, 2023

Keywords:

Ground fault
Grounding system
Inductive coupling
Reduction factor
Screening factor
Series impedance

ABSTRACT

The presented methodology enables determining induced currents and voltages relevant to the correct estimation of security conditions required in operating and maintenance of the metal installations surrounding high-voltage distribution cable lines. It is based on the on-site measurements of currents appearing in two phase conductors of the considered cable line during a simulated ground fault in the supplied substation. Their values are utilized to compensate for the deficiency of all relevant but unknown data concerning the surrounding metal installations. It was done by introducing an equivalent cable shield substituting, from the standpoint of inductive influence, all surrounding metal installations. Here is shown that this equivalent shield can be determined in such a way that it becomes identical from the standpoint of its appearance to the actual cable line shield but with a changed value of its longitudinal resistance. When this value is determined for single-core cables belonging to a certain cable line it becomes possible to determine the actual reduction factor, inductive influence, and sequence impedance of the considered cable line by using a standard and well-known calculation procedure.

Corresponding Author:

Ljubivoj M. Popović
J. P. Elektrodistribucija-Beograd, Elektroprivreda Srbije
Masarikova 1-3, 11000 Beograd, Serbia
Email: ljubivoje@beotel.net

1. INTRODUCTION

The electromagnetic influence of electric-power lines on nearby metal installations (communication lines or different metal pipelines) has been the subject of investigations for at least the last, six decades. In urban areas where many different metal installations are laid at a relatively small distance from each other the induced voltages can endanger the safety of the public and field workers in large urban areas along and around these lines. Because of that the values of the induced voltages have to be within certain prescribed limits [1]. Besides the safety problems, induced voltages can cause corrosion on the surface of pipelines, and other types of metal installations typical for urban areas. In the case of pipelines, if the coating is not sufficiently resistant to withstand the possible stress exerted by induced voltages, it can lead to mechanical damage and poor functioning. Because of that the magnitude of the induced voltages should be determined in all, practically possible situations. Only on the basis of their correctly determined values, it is possible to prevent all, undesirable (dangerous and harmful) consequences by applying adequate protection measures. Of course, the greatest problems can be expected in the case of lines through whose phase conductors the current can reach the highest values during fault conditions or normal operation. In modern distribution networks, such lines are high voltage (HV) and extra high voltage (EHV) cable lines.

However, the circumstance that these lines are usually laid in highly urbanized areas with a large number of different metal installations has also certain favorable effects. The vast majority of these installations are grounded at least at their ends, so induced currents occur in these installations, which also create their own electromagnetic fields. These fields partially cancel the electromagnetic field generated by the considered cable line and thus reduce the unfavorable inductive influence on each of the surrounding metal installations observed individually. The currents induced in the surrounding metal installations also reduce the part of the ground fault current that is injected into the surrounding earth through the grounding system of the supplied substation. Thus, the potentials that can appear on the grounding systems of supplied substations are also reduced. Therefore, in order to estimate correctly the magnitude of the considered problems in each specific case, it is necessary to have a methodology that allows taking into account the effects of each of the currents that are induced in the surrounding metal installations. By using relatively simple calculation procedures presented in the corresponding technical standards this is the most frequently not possible to do [2], [3].

Many so-far-published papers propose different methods developed with the aim to enable taking into account as many possible factors and parameters relevant to different situations that can be encountered in practice e.g. [4]–[12]. The possibilities of the methods developed in the past for determining the currents and voltages induced in the exposed metal installations are separately considered and valuated in [4]. Recently developed methods are based on computer software to achieve as accurate a possible simulation of the considered phenomenon in very complex practically possible situations. For example, the methods presented in [11] and [12] enable taking into account a large number of different pipelines, power lines, bonds, groundings, and coating. The common characteristic of these methods is that they enable taking into consideration the constructive characteristics and mutual space position of all installations in the arrangement, as well as the characteristic of the surrounding earth as a conductive medium. However, none of them enables a solution when the problem appears in urban areas, i.e. there, where many relevant data concerning the surrounding metal installations are uncertain or completely unknown.

The considered problem in urban conditions has become solvable by developing the methodology presented in [13]. The solution was achieved on the basis of experimental investigations and an analytical procedure that enables substituting all surrounding metal installations, from the standpoint of their inductive influence, with only one equivalent conductor. The physical appearance and spatial position of this fictitious conductor are such that it represents a cylinder surrounding all conductors of one HV or EHV line along the entire length of this line. The results of the mentioned investigations show that the fraction of the ground-fault current flowing solely through the earth, in a typical urban environment, is three to five times smaller than it has been considered before. Certainly, this fact throws completely new light on the whole grounding problem of HV distribution substations supplied by cable lines and dramatically changes our earlier perception of its magnitude.

Somewhat later the method presented in [13] was improved in such a manner that the mentioned equivalent conductor besides all surrounding metal installations substitutes also all metal shields of the considered line [13]–[17]. It has been imagined as a cylinder that surrounds only the phase conductor with a simulated (or actual) ground-fault current. As well as in the previous case, this conductor is completely defined by only two parameters. One of them is the radius of this fictitious conductor, whereas the other one is its longitudinal resistance. However, the methodology developed in [13]–[17] was not applicable in the case of HV cable lines with applied cross-bonding, required for all HV and EHV distribution cable lines [18]. In that case, the cable line metal shields are mutually cross-bonded at certain places along the line so that the problem of ground-fault current distribution becomes so complex that cannot be solved without the application of a computer even if we disregard all surrounding metal installations [19]. The considered problem, in this, in practice the most common and the most complex case, becomes solvable by introducing an additional phase conductor in the foreseen measurement procedure as shown in [20]–[22]. However, the imagined equivalent shields have spatial positions (radius) changed in comparison to the positions (radius) of actual shields of HV and EHV cable lines. This fact creates certain confusion in the application of the methodology for solving different problems of the inductive influence of HV and EHV distribution cable lines and that is the problem that should be overcome.

In this paper methodology for compensation for the deficiency of many relevant but unknown data (or Popović's methodology) [13]–[17] and [20]–[22] has been improved in such a way that enables taking into account the inductive influence of all surrounding metal installations only through the changed value of longitudinal resistance of actual cable line shields. When we obtained this value for one and all three metal shields of a certain cable line we can determine the actual reduction factor, actual inductive influence, and actual sequences (ground fault current) in this line by using a standard or well-known calculation procedure, e.g. [2], [3], [23].

2. METHODOLOGY

2.1. Main ground fault current fractions

In urban and suburban areas power distribution cable lines share the same streets with many different metal installations typical for urban surroundings so mutual electromagnetic interaction between them is practically unavoidable. Due to this, the surrounding metal installations spontaneously acquire the function of additional neutral conductors of these power lines, and they together with conductors of these lines form one very complex electrical circuit. For a better understanding of the participation of the surrounding metal installations in one such circuit formed during a ground fault in a supplied HV substation, the main fractions of a ground-fault current can be presented as shown in Figure 1.

The grounding systems of HV/MV distribution substations consist of the substation grounding electrode and many outgoing MV (medium voltage) cable lines acting as external grounding electrodes, and/or conductive connections with the grounding systems of the supplied MV/LV substations. In this way, the metal shields of the outgoing MV cable lines spontaneously obtain a rule of conductive connections with the metal installations surrounding the feeding line of these substations [24]. Based on Figure 1, it is not difficult to notice that in the case of a ground fault in the supplied substation, two ground-fault current fractions appear outside of the power system. One of them, current I_e, is dissipated into the surrounding earth through the grounding system of substation B, while the other, current I_{mi} is induced in the surrounding metal installations that are not foreseen for this purpose. Therefore, it can be said that all public safety and certainty problems are caused by these two currents. Because of that, their values should be determined in each specific case of an HV or EHV cable line. Only when we know their values we can determine the voltage that can be induced in some of the surrounding installations as well as the potential that can appear on the grounding system of the supplied substation, that is, on the metal installations coming out of this substation.

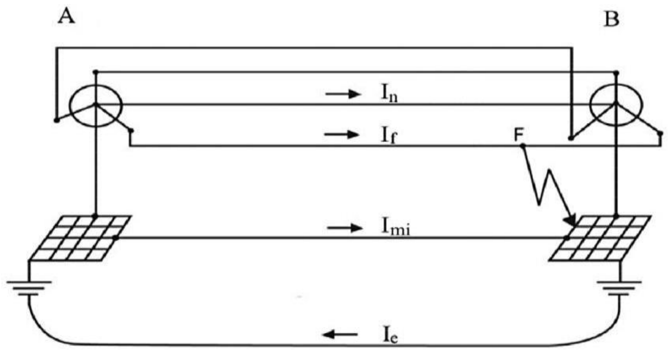

Figure 1. A ground-fault current and its main parts [15]

The notation used has the following meaning:
- A (B): Supply (supplied) substation;
- F: Ground fault location (supplied substation);
- I_f: A ground-fault current component coming from substation A;
- I_n: A ground-fault current fraction circulating through the line neutral conductors;
- I_{mi}: A ground-fault current fraction induced in the metal installations surrounding the feeding line;
- I_e: A ground-fault current fraction dissipated through the grounding system of substation B into the surrounding earth.

Since the mutual separation of currents, I_{mi} and I_e occur along many external grounding electrodes (metal shields of outgoing MV cable lines) and under the surface of the ground, none of these currents can be determined by calculations or by measurements [24]. Also, many of the metal installations surrounding a feeding line are grounded at both ends and each of them, with the earth as the common return path, forms one closed electrical circuit. Therefore current I_{mi} has been divided into many smaller fractions that differently affect the value of the potential induced at the opposite end of some surrounding metal installation that is in the moment of a ground fault grounded at only one end.

Besides, it is necessary to say, an unbalanced current existing under normal operating conditions also uses the same return paths as the ground fault current. Although it is, of course, significantly smaller than the ground-fault current its flow is long-lasting, and because of that its influence can also be harmful and disturbing for sensitive electronic systems embedded in this network by upsetting data transmission. Thus for the correct solving of the mentioned problems, it is necessary to analyze a completely formed electrical circuit with all its, known and unknown, elements.

2.2. All induced currents

With the aim to obtain a complete equivalent circuit let us assume an HV or EHV cable line with no applied cross-bonding and in the most general case, from the standpoint of their spatial formation, as is shown in Figure 2.The used notation has the following meaning: i) d – the distance between two adjacent cables, and ii) r_{sh} – mean radius of the cable shield. Then assuming an arbitrary number of the surrounding metal installations the complete electrical circuit formed by the adopted cable line, during a simulated ground fault in supplied substation B, can be presented as shown in Figure 3.

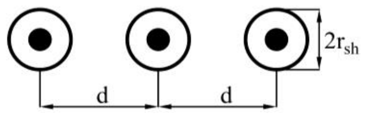

Figure 2. Single-core cables laid in a flat formation

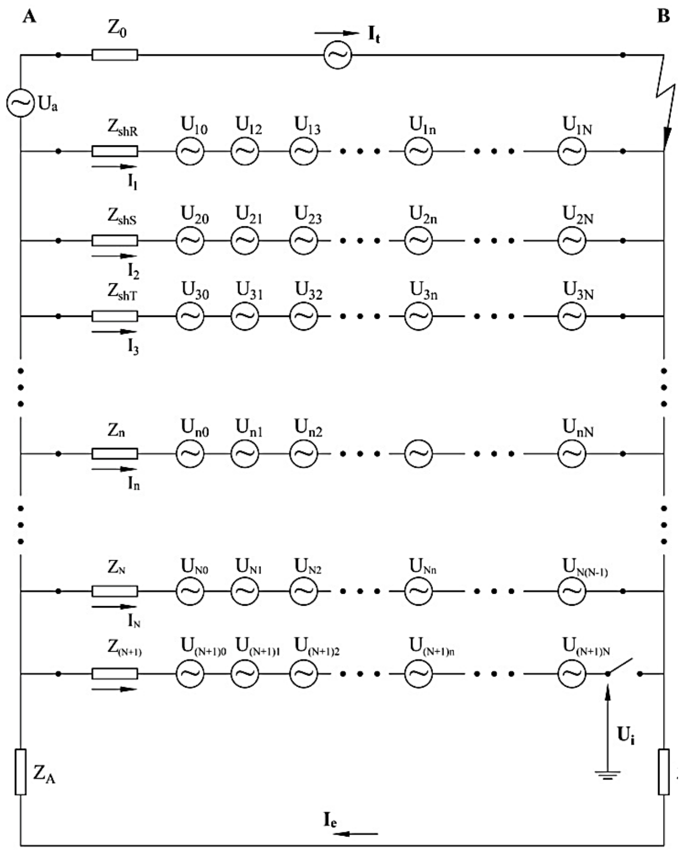

Figure 3. Complete equivalent circuit [20]

The used notation has the following meaning:
- A (B): Supply (supplied) substation;
- U_a: Auxiliary voltage source;
- U_{n0}, U_{n1}, U_{n2}, …, U_{nN}: Voltages induced in an arbitrary (nth) metal installation by the current in each of the surrounding electrical conductors/circuits;
- I_t: Simulated ground-fault current through one of the phase conductors of the considered line;
- I_1: Current induced in the shield of the single-core cable carrying test current I_t,;
- I_2, I_3: Currents induced in the shields 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 applied phase conductor of the considered cable line;
- Z_{sh}: Self-impedances of the cable shields;
- Z_4, Z_5, Z_6, …, Z_N: Self-impedances of the individual surrounding metal installations;
- N: An arbitrarily large number of currents induced in surrounding metal installations and the shields of the considered cable line:

- N+1: An arbitrary metal installation grounded at only one end; and
- U_i : Voltage/potential induced in (N + 1)-th installation.

As can be seen, the presented equivalent circuit is composed of the self-and mutual impedances of all surrounding metal installations and all shields of the adopted cable line including the phase conductor carrying current I_t. The self-impedance of an arbitrary, n^{th}, surrounding the metal installation of a cylindrical shape can be, according to e.g. [2], determined by (1),

$$Z_n' = R_n' + \omega_t \frac{\mu_0}{8} + j\omega_t \frac{\mu_0}{2\pi} ln \frac{\delta_t}{r_n}, \Omega/\text{km}, \quad (1)$$

where as in the case of the installation with a full metal cross-section, is:

$$Z_n' = R_n' + \omega_t \frac{\mu_0}{8} + j\omega_t \frac{\mu_0}{2} (\frac{\mu_r}{4} + ln \frac{\delta_t}{r_n}), \Omega/\text{km} \quad (2)$$

The mutual impedance between two arbitrary, n^{th} and m^{th}, surrounding metal installations is, according to e.g. [2], determined by (3).

$$Z_{nm}' = \omega_t \frac{\mu_0}{8} + j\omega_t \frac{\mu_0}{2\pi} ln \frac{\delta_t}{d_{nm}}, \Omega/\text{km};\ m \neq n \quad (3)$$

Where:
- R'_n : Longitudinal resistance of an arbitrary, n^{th}, surrounding metal installation (Ω/km);
- r_n: Mean radius of an arbitrary, n^{th}, surrounding metal installation (m);
- d_{nm}: The distance between two arbitrary, n^{th} and m^{th}, surrounding metal installations (m);
- ω_t: Angular test frequency: $2\pi f_t$;
- μ_0: Magnetic permeability of vacuum: $4\pi \cdot 10^{-7}$ Vs/Am;
- μ_r: Relative magnetic permeability of the metal installation;
- δ_t: Equivalent earth penetration depth (m).

The equivalent earth penetration depth is determined by (4).

$$\delta_t = 658\sqrt{\frac{\rho}{f_t}}, (\text{m}) \quad (4)$$

Where:
P: Equivalent soil resistivity along and around the considered cable line (Ωm); and
f_t: Test circuit frequency (somewhat higher than power frequency [13]).
Current in an arbitrary surrounding installation, I_n (Figure 3), induces in an also arbitrary (m^{th}) surrounding installation a voltage, U_{mn}, which is determined by (5).

$$U_{mn} = -Z_{nm}' I_n, m \neq n \quad (5)$$

Where Z'_{nm}: mutual impedance between the m^{th} and n^{th} surrounding metal installation.

Although complete, from the standpoint of the number of elements, the presented equivalent circuit is not without any idealization and approximation in relation to the electrical circuit formed in reality. For example, the fact, that some of the metal installations are grounded at certain places, mainly in each of the buildings arranged along both sides of streets, has been disregarded. However, according to the considerations presented in [20]–[22], this fact is not relevant for determining the currents induced in these installations. For the same reason, the capacitive effects of an HV or EHV line are not relevant for determining these currents [21].

Also, in urban conditions, the surrounding metal installations usually are not laid strictly in parallel with an HV or EHV cable line and mutually along its whole length. However, unlike other known methodologies for determining the inductive influence of power lines, their mutual spatial positions are not necessary for the application of the methodology presented in [20], [22]. Accordingly, this methodology is applied in the same way to cable lines with applied cross-bonding as to lines where this technique is not applied. All this can be concluded based on the considerations presented in [21], [24].

Finally, the value of the equivalent soil resistivity, ρ, in urban areas can be only approximately estimated based on the main geological characteristics of the soil surrounding the considered cable line [19]. However, according to (1), (2), and (3), this approximation has not any notable influence on the accuracy of (1), (2), and (3) because impedances Z'_n and Z'_{nm} are only slightly dependent on the soil resistivity, ρ.

Based on the circuit in Figure 3 it is obvious that the current I_t and all induced currents contain a cumulative effect of the inductive couplings with all other spontaneously formed electrical circuits. This fact enables us to solve the problem of the deficiency of many relevant data only by measuring the test current and current induced in the shield with the test current, I_1 (Figure 3) [13], [16]. However, somewhat later was shown that it is better from the standpoint of the applicability and accuracy of this methodology to use one more phase conductor instead of the mentioned shield [20]–[22]. For that purpose, this additional phase conductor has to serve as one more neutral conductor and has been named an "additional phase conductor".

2.3. Necessary measurements

By introducing an additional phase conductor the necessary measurements in the case of the cable line with applied cross-bonding are performed, according to [20]–[22], by using the measurement circuit shown in Figure 4.

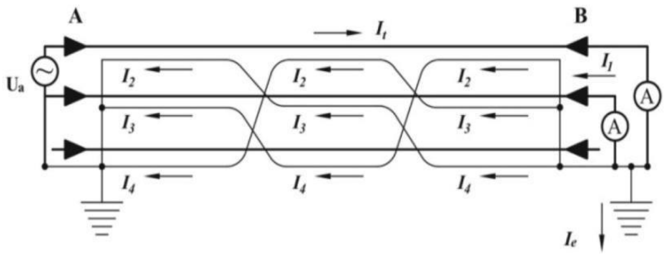

Figure 4. The principal measurement circuit [20]

The used notation has the following meaning:
- U_a: Auxiliary voltage source;
- I_t: Test (simulated ground fault) current;
- I_1: Current induced in the additional phase conductor;
- I_e: Current injected into the earth through the grounding system of substation B;
- I_2, I_3, and I_4: Currents induced in the individual cable line shields;
- A: Ampere-meter.

In accordance with the considerations given in [20], and [22] a slightly higher accuracy of the methodology is achieved when there is a stronger inductive coupling between the used phase conductors. Because of that the phase conductor that is closer to the phase conductor with simulated ground-fault current is used as an additional phase conductor.

2.4. Relevant parameters of the equivalent shield

By using the mentioned equivalent conductor (in the further text: equivalent shield) substituting all surrounding metal installations including three shields of the considered line, the equivalent circuit of this line during the simulated ground fault becomes significantly simpler as shown in Figure 5. As can be seen, in this circuit the grounding impedances at the ends of the line are disregarded ($Z_A \approx Z_B \approx 0$), since they are relatively small in urban conditions, e.g. [25], [26]. In that way, we take into consideration only the mutual inductive coupling between the phase conductor with test current I_t on one side and each of the surrounding metal installations including the shields of the considered line on the other side at determining required quantities: I_e and U_i (Figure 3). As is well known, current I_e is relevant for potentially hazardous and harmful potentials and potential differences that appear on the grounding system of the supplied substation, whereas voltage U_i is relevant for hazardous and harmful voltage that can be induced in an arbitrary (N + 1)-th installation. The used notation has the following meaning:
- U_{10} (U_{1eq}): Voltage that current I_t (I_i) induces in the additional phase conductor with I_1;
- U_{eq0} (U_{eq1}): Voltages that current I_t (I_1) induces in the equivalent shield;
- I_i: Current induced in the equivalent shield;
- Z_{ph}: Self-impedance of the phase conductor (Ω);
- Z_{eq}: Self-impedance of the introduced equivalent shield (Ω).

Based on the equivalent circuits in Figure 3 and 5 it is obvious that the arbitrarily large number (N) of unknown currents through all of the surrounding metal installations including shields of the considered line are reduced to only one current, I_i. Also, numerous known and unknown surrounding metal installations including shields of the considered line are substituted by only one equivalent shield. The relevant parameters of this equivalent shield can be determined by using the following condition: currents I_t, I_1, and I_e in Figures 3 and 5 have to remain unchanged after introducing the equivalent shield. According to the equivalent circuit in Figure 5, this condition can be expressed by the following system of equations:

$$Z'_{01}I_t + Z'_{ph}I_1 + Z'_{1eq}I_i = 0$$
$$Z'_{0eq}I_t + Z'_{1eq}I_1 + Z'_{eq}I_i = 0 \tag{6}$$

where:
Z'_{eq}: Self-impedance of the equivalent shield (Ω/km);
Z'_{0eq}: Mutual impedance between the equivalent shield and the phase conductor with current I_t (Ω/km);
Z'_{1eq}: Mutual impedance between the equivalent shield and the additional phase conductor (Ω/km).
Impedances Z'_{ph} and Z'_{01} are, according to [1], determined by:

$$Z'_{ph} = R'_{ph} + \omega_t \frac{\mu_0}{8} + j\omega_t \frac{\mu_0}{2}\left(\frac{\mu_r}{4} + ln\frac{\delta_t}{r_{ph}}\right), \text{ Ω/km}, \tag{7}$$

$$Z'_{01} = \omega_t \frac{\mu_0}{8} + j\omega_t \frac{\mu_0}{2\pi} ln\frac{\delta_t}{d}, \text{ Ω/km}, \tag{8}$$

where
R'_{ph} – longitudinal resistance of the phase conductor, (Ω/km),
r_{ph} – radius of the phase conductor (m),
ω_t – angular test circuit frequency: $2\pi f_t$,
μ_r – relative magnetic permeability of the phase conductor,
d – the distance between two adjacent single-core cables (m).

Based on the system of equations (6), it is interesting to note that the relative ratio between the currents I_t, I_1, and I_i, does not depend on the voltages induced in the phase conductor with current I_t. It means that the voltages U_{to} and U_{teq} from the equivalent circuit in Figure 5 are not relevant in solving the considered problem and can be omitted from this circuit. On the basis of the considerations presented in [21], [24], the equivalent shield can be determined for any arbitrarily adopted value of its radius, r_{eq}. According to that, the considered cable line and all surrounding metal installations during a simulated ground fault can be presented by a relatively simple and known cable model whose cross-section is shown in Figure 6.

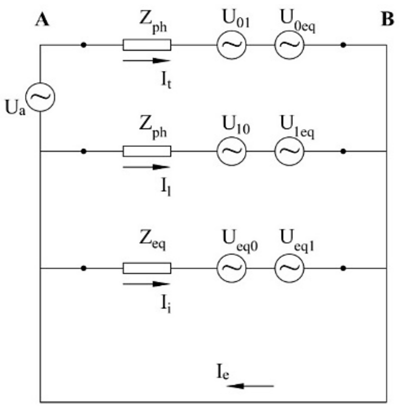

Figure 5. Simplified equivalent circuit [21]

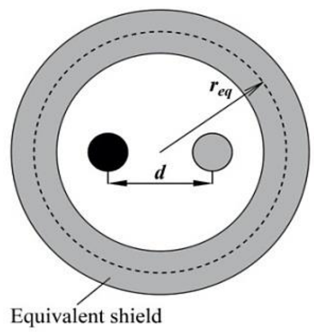

Figure 6. Cross-section of the introduced cable model [19]

The additional phase conductor in this figure is denoted differently (lighter shaded) to show that for the necessary measurements, it serves as one more neutral conductor. Since the considered cable line can be considered as a single-core cable (Figure 6), the analytical expressions for impedance Z'_{eq}, Z'_{0eq}, and Z'_{1eq} are known in advance and, according to [2], determined by (9).

$$Z'_{eq} = R'_{eq} + \omega_t \frac{\mu_0}{8} + j\omega_t \frac{\mu_0}{2\pi} ln\frac{\delta_t}{r_{eq}}, \text{ Ω/km}, \tag{9}$$

$$Z'_{0eq} = Z_{1eq} = \omega_t \frac{\mu_0}{8} + j\omega_t \frac{\mu_0}{2\pi} ln \frac{\delta_t}{r_{eq}}, \Omega/\text{km}, \quad (10)$$

Where:
- R'_{eq}: Longitudinal resistance of the equivalent shield (Ω/km); and
- r_{eq}: Mean radius of the imagined cylinder representing the equivalent shield (m).

Also, since currents I_t and I_1 are obtained by measurements, they can be considered as in advance known quantities, and the system of (6) can be presented in the following manner:

$$\frac{Z'_{0eq}Z'_{1eq} - Z'_{eq}Z'_{01}}{Z'_{eq}Z'_{ph} - Z'^2_{1eq}} = \frac{I_1}{I_t} \quad (11)$$

Then, since (11) gives the relationship between complex quantities, it can be presented in one more form:

$$\begin{aligned} Re \quad & \{(Z'_{0eq}Z'_{1eq} - Z'_{eq}Z'_{01})I_t\} = Re\left\{\left(Z'_{eq}Z'_{ph} - Z'^2_{1eq}\right)I_1\right\} \\ Im \quad & \{(Z'_{0eq}Z'_{1eq} - Z'_{eq}Z'_{01})I_t\} = Im \quad \left\{\left(Z'_{eq}Z'_{ph} - Z'^2_{1eq}\right)I_1\right\} \end{aligned} \quad (12)$$

where Re and Im are the denotations for the real and imaginary parts of (11).

In the system of (12), the only unknown quantities, according to (7), (8), (9), and (10), are R'_{eq} and r_{eq}. Thus by solving this system of equations, we obtain the values of the required parameters of the equivalent shield, R'_{eq}, and r_{eq}. Then, for obtaining the actual reduction factor [14] (or resulting screening factor [3]) of the considered cable line we can use the analytical expression for this factor when a cable line has been performed with only one single-core cable. Or, in accordance with e. g. [24], we can write (13).

$$r_a = k_r = \frac{R'_{eq}}{R'_{eq} + \omega\frac{\mu_0}{8} + j\frac{\omega\mu_0}{2\pi} ln\frac{\delta}{r_{eq}}} \quad (13)$$

Based on (13) unknown induced voltage/potential U_i can be determined by (14).

$$U'_i = -k_r Z'_{(n+1)0} I_f \quad (14)$$

Whereas voltage/potential on the grounding system of the supplied substation is (15).

$$U_{gs} = r_a Z_B I_f \quad (15)$$

Where I_f is anticipated actual ground fault current in substation B. Here it should be mentioned that these two voltages can be superposed in some of the installations outgoing from the supplied substation.

Based on approximations $Z_A \approx Z_B \approx 0$, each current appearing in the additional phase conductor (Figure 4) or in any other of the surrounding installations/conductors is a consequence solely of the mutual inductive couplings of each of them with all other of them (Figure 3). However, currents I_t and I_1 are determined by measurements i.e. by taking into account the actual values of grounding impedances Z_A and Z_B. This certainly compensates to some extent the inaccuracy caused by the formerly mentioned approximations.

Also, the value of equivalent soil resistivity, necessary for the application of this methodology, should be adopted as the lowest one, among several ones approximately estimated based on the main geological characteristics of the surrounding urban area. Certainly, in this way, the favorable inductive influence of the surrounding metal installations becomes slightly lower.

Since the spatial positions of the individual single-core cables in relation to the surrounding metal installations are not identical, the presented procedure should be applied to each of the phase conductors of the considered line. Then, for enlarged safety, we should adopt those parameters (R'_{eq} and r_{eq}) that correspond to the smallest inductive influence of the surrounding metal installations.

However, certain confusion in the application of the parameters of the equivalent sheath, R'_{eq}, and req, represents the fact that the mean radius req of the equivalent cable shields is larger than the actual ones (Figure 2). So, in the calculations where it is necessary to replace one equivalent shield with 3 equivalent shields, they would partially overlap if the single-core cables of the considered line are in the triangular formation.

3. IMPROVEMENT OF THE METHODOLOGY BY INTRODUCING EFFECTIVE SHIELDS

3.1. Effective shield for determining actual reduction and resulting screening factor

On the basis of the considerations given in [15], [19], each of the cable line shields and each of the surrounding metal installations grounded at both ends can be considered as one short-circuited ”secondary turn” of one spontaneously formed and specific transformer of huge dimensions. By introducing an equivalent shield such as a specific transformer, in fact, an HV or EHV cable line and surrounding metal installations during a simulated ground fault (Figure 3), can be presented, according to [21], [24], as shown in Figure 7. The used notation has the meaning: F_r is resultant alternating magnetic flux through the ”primary and secondary turn”.

On the basis of Figure 7, it is not difficult to see that for the certain value of I_t, resultant flux F_r depends only on the spatial position of the introduced equivalent shield (”equivalent secondary turn”) in relation to the phase conductor (”primary turn”), defined by r_{eq} (mean radius of equivalent shield), and current through the introduced equivalent shield, I_i. According to this an arbitrarily large number of the mutually different shields (different combinations of parameters r_{eq} and R'_{eq}), seen separately, can create the same value of resulting flux F_r. This means that for any in-advance adopted value of r_{eq}, we can determine corresponding R'_{eq} also satisfying the required condition that the resulting flux and current I_e remains unchanged. Thus by assuming that the spatial position of the equivalent shield is such that coincides with the actual shield of the single-core cable with test current, I_t, instead of parameters r_{eq} and R'_{eq}, we have only parameter $R'_{eq}(r_{eq} = r_{sh})$. At this, for obtaining the corresponding value of R'_{eq}, one uses expression (13).

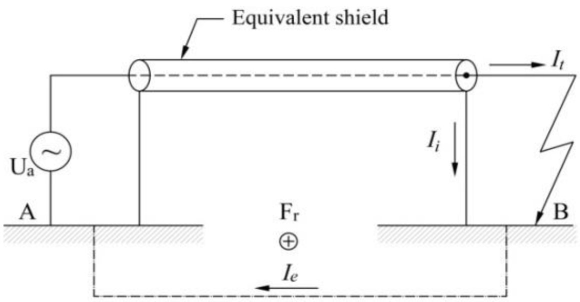

Figure 7. Simplified cable line model [21]

According to this, the favorable inductive influence of all surrounding metal installations including the shields of the other two single-core cables can be expressed only through the corresponding value of the longitudinal resistance of the shield of the single-core cable with test current. With the aim to make the difference in relation to all other also equivalent shields of a certain phase conductor of the considered cable line this equivalent shield, we will call the effective shield. It can be defined as a cable shield that instead of the real one has an effective (computational) longitudinal resistance through whose value the inductive influences of all surrounding metal installations including the other two shields of the considered line are taken into account.

Based on Figures 3, 4, and 7, it is obvious that by introducing the equivalent or effective shields the line with applied cross-bonding is reduced from the point of view of further calculations to a simpler case of lines at which this technique has been not applied. Thus, in the case when we have to determine the inductive influence of a certain cable line during faulty conditions we reduce the problem to the simplest case where we have in the whole surroundings only one single-core cable and only one induced installation. Also, when we have to determine the inductive influence of a certain cable line in normal operation by determining the effective shield for all three single-core cables we reduce the whole problem to the simplest case where we have three inducing single-corer cables and only one induced installation. So in both cases, further calculations can be performed by using the standard calculation procedure [3]. Also, the known effective shield allows us to solve a problem that can appear by laying one or more new surrounding installations whose relevant data are known. It can be done by a well-known calculation procedure used to obtain one equivalent neutral conductor substituting two or more neutral conductors of a certain line.

Finally, based on the previous considerations, it is not difficult to see that it is possible to determine the corresponding effective shields for determining the inductive influence on any of the surrounding metal installations (Figure 3) during faulty and normal operating conditions. Although they refer to the same inducing cable line they are different for each of these installations. When they are determined the further calculation procedure is reduced in all cases to the simplest case solvable by using the corresponding technical standard, [3].

3.2. Effective shields for determining the actual sequence impedances

Surrounding metal installations due to their inductive influence increases the value of the total ground fault current in the supplied substation, I_f, and because of that they should not be disregarded [16], [20], [24]. However, the previously defined effective shield is not adequate for obtaining the sequence impedances of the considered line. Namely, its use the influence of the surrounding metal installations on the magnitude of the ground fault current would be taken into account three times. Thus for this purpose, it is necessary to convert the previously determined effective shield into three equivalent shields, one for each of the 3 single-core cables. The relevant parameters of the three equivalent sheaths for cables laid in the triangular formation are, according to e.g. [24], determined by:

$$R'_{eq3} \text{ and } r_{eq_3} = 1/\sqrt[3]{4} r_{sh} \tag{16}$$

Then, using (13) we can from R'_{eq} and r_{eq} determine the effective longitudinal resistance for all 3 single-core cables, R'_{eq3}.

When parameter R'_{eff3} is determined the influence of all surrounding metal installations is involved through all three shields of the considered cable line. Then its sequential impedances are obtained by applying a well-known calculation procedure that refers to the case when there are only conductors of the considered line in the entire environment [23]. It is only necessary to replace the real parameter R'_{sh} with the parameter $R'_{eff3.}$ For this type of calculation, the values of R'_{eq} and r_{eq} should be adopted so that they refer to the case of the single-core cable with the greatest inductive influence of the surrounding metal installations. In this way, it is achieved that the obtained value of the ground-fault current in the supplied substation is slightly greater than the actual one.

4. RESULTS AND DISCUSSION

With the aim of obtaining an insight into the possible magnitudes of the value of the longitudinal resistance of an effective shield, we will use the results of the experimental investigations performed in the 110 kV distribution network of Beograd [13]. For these investigations has been used a cable line with single-core cables laid in a trefoil formation along the whole length and with no applied cross-bonding technique. Their metal shields are made of copper strings having a total cross-section of 95 mm^2, and the mean diameter is equal to 91 mm. It supplies substation B from source substation A via transit substation C.

According to the results of the mentioned investigations, the relevant parameters of the equivalent shield substituting only surrounding metal installations are the following:

- For the entire feeding line: $R'_{eq} = 0.053$ Ω/km and $r_{eq} = 8.1$m,
- For the section from substation A to substation C: $R'_{eq} = 0.08$ Ω/km and $r_{eq} = 12.3$ m,
- For the section from substation C to substation B: $R'_{eq} = 0.031$ Ω/km and $r_{eq} = 7.1$ m.

Based on these results and the relevant data about the equivalent shield substituting all three cable shields (obtained by relations: $R'_{eq3sh}=0.333\, R'_{sh}$ and $r_{eq3sh}=1.587\, r_{sh}$) and by using the calculation procedure presented in [19], the resulting screening factors have the following values:

$$k_{AB} = -\,0.026 - j0.023;\ k_{AC} = -\,0.018 - j0.012 \text{ and } k_{CB} = -\,0.031 - j0.037.$$

Based on these results and (13) one obtains that the corresponding longitudinal resistances of the effective shields for the considered line and its sections are the following:

$R'_{effAB}(r_{eq} = 0.0455\text{m}) = (0.01324 - j0.01726)$ Ω/km,
$R'_{effAC}(r_{eq} = 0.0455\text{m}) = (0.02191 - j0.02128)$, Ω/km, and
$R'_{effCB}(r_{eq} = 0.0455\text{m}) = (0.00659 - j0.01138)$, Ω/km.

Since the single-core cables of the considered line are laid in the trefoil formation i.e. on the minimal mutual distances these values can be considered relevant with a small approximation for each of the three single-core cables. By using these values we can determine the inductive influence of this line and its sections during normal operation conditions by superposing the voltages or currents induced by the current in each of the phase conductors e.g. [3]. This way of calculations, because of the unchanged positions of cable shields, certainly, enables a better understanding of the methodology in comparison with its earlier version

[20]. Of course, the described calculation procedure can also be used in cases when there are several inducting cable lines in the same urban environment.

As can be seen, the longitudinal resistance of an effective shield has a complex value and as such, of course, does not exist in reality. However, by introducing such value of a longitudinal resistance into the presented analytical procedure, the problem of the inductive influence of currents in the phase conductors of one or more cable lines with applied cross-bonding is reduced, from the standpoint of necessary calculations to the simplest case. That is the case when in the whole environment, in addition to the inducing cable line (or lines) transformed into the line with no applied cross-bonding there is only one induced installation.

When we have to determine the sequence impedances of a cable line with no applied cross-bonding [16] by using the effective cable shields, then all three cable line shields seen together, that is as a whole have to encompass the inductive influence of surrounding metal installations. Thus in that case the equivalent shield substituting all surrounding metal installations should be transformed into three equivalent shields whose parameters are determined by (16). Then by using the previous calculation procedure, we obtain three effective shields of the considered cable line, and its sections are determined by the following longitudinal resistance:

$R'_{\text{eff3AB}}(r_{\text{eq}} = 0.0455\text{m}) = (0.0987 - j0.0468)\ \Omega/\text{km}$,
$R'_{\text{eff3AC}}(r_{\text{eq}} = 0.0455\text{m}) = (0.1208 - j0.0455)$, Ω/km, and
$R'_{\text{eff3CB}}(r_{\text{eq}} = 0.0455\text{m}) = (0.0681 - j0.0375)$, Ω/km, seen respectively.

By using the effective shields in this case the considered problem is also reduced to the simplest case when in the whole environment only this 110 kV line exists (e.g. [23]).

Concerning the whole methodology [13]–[17], [20]–[22] it is important to note the following: Between an unlimited number of different equivalent shields that can be obtained using (13), only one obtained by (12) has a value of the longitudinal resistance that is expressed by a real number i.e. that corresponds to this physical property of electrical conductors.

5. CONCLUSION

The paper presents a certain improvement of the methodology that enables taking into consideration the inductive influence of all metal installations surrounding HV or EHV cable lines only through the value of the longitudinal resistance of the here-defined effective cable shield. By using effective shields the spatial position and appearance of single-core cables belonging to the considered line are identical to the appearance of actual ones. Thanks to this when we determined the effective shields the determination of the actual reduction factor, inductive influence, and sequence impedances of any cable line passing through urban and/or suburban areas reduce to the simplest cases solvable by standard and well-known calculation procedures.

REFERENCES

[1] NACE International, "Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems," *NACE International*, vol. SP0177, no. 21021. p. 25, 2007.

[2] IEC, "INTERNATIONAL STANDARD Short-circuit currents in three-phase AC systems – Part 3: Calculation of currents (IEC 60909-3:2016)," *Iec 60909-3*, vol. Edition 3., 2009.

[3] CCITT, "Directives Concerning the Protection of Telecommunication Lines Against Harmful Effects from Electric Power and Electrified Railway Lines," *International Telecommunication Union*, 1990.

[4] M. Purcar, C. Munteanu, V. Topa, L. Grindei, and ..., "Actual Stage of the Research Regarding the AC Interferences on Common Corridors," *Acta electrotehnica*, 2009, [Online]. Available: https://ie.utcluj.ro/files/acta/2009/Number4/Paper11_Purcar.pdf.

[5] J. Pohl, "Influence of High-Voltage Overhead Lines on Covered Pipelines," *Cigre*, 1966.

[6] F. Dawalibi and A. Pinho, "Computerized Analysis of Power Systems and Gas Pipelines Proximity Effects," *IEEE Power Engineering Review*, vol. PER-6, no. 4, pp. 29–30, 1986, doi: 10.1109/MPER.1986.5527710.

[7] S. T. Sobral, W. G. Castinheiras, M. M. Nielsen, V. S. Costa, and D. Mukhedkar, "Interferences between faulted power circuits and communication circuits or pipelines-simplification using the decoupled method," *IEEE Transactions on Power Delivery*, vol. 6, no. 4, pp. 1599–1606, 1991, doi: 10.1109/61.97698.

[8] K. J. Satsios, D. P. Labridis, and P. S. Dokopoulos, "The influence of multi-layer ground on the electromagnetic field of an overhead power transmission line in the presence of buried conductors," *Electrical Engineering*, vol. 80, no. 5, pp. 343–348, 1997, doi: 10.1007/BF01370971.

[9] G. Djogo and M. M. A. Salama, "Calculation of inductive coupling from power lines to multiple pipelines and buried conductors," *Electric Power Systems Research*, vol. 41, no. 1, pp. 75–84, 1997, doi: 10.1016/s0378-7796(96)01162-5.

[10] D. A. Tsiamitros, G. K. Papagiannis, and P. S. Dokopoulos, "Homogenous earth approximation of two-layer earth structures: An equivalent resistivity approach," *IEEE Transactions on Power Delivery*, vol. 22, no. 1, pp. 658–666, 2007, doi: 10.1109/TPWRD.2006.881465.

[11] L. Bortels, J. Deconinck, C. Munteanu, and V. Topa, "A General Applicable Model for AC Predictive and Mitigation Techniques for Pipeline Networks Influenced by HV Power Lines," *IEEE Transactions on Power Delivery*, vol. 21, no. 1, pp. 210–217, Jan. 2006, doi: 10.1109/TPWRD.2005.848754.

[12] G. C. Christoforidis, D. P. Labridis, and P. S. Dokopoulos, "Inductive Interference on Pipelines Buried in Multilayer Soil Due to Magnetic Fields From Nearby Faulted Power Lines," *IEEE Transactions on Electromagnetic Compatibility*, vol. 47, no. 2, pp. 254–262, May 2005, doi: 10.1109/TEMC.2005.847399.
[13] L. M. Popović, "Testing and evaluating grounding systems for substations located in urban areas," *IET Generation, Transmission and Distribution*, vol. 5, no. 2, pp. 231–238, 2011, doi: 10.1049/iet-gtd.2009.0665.
[14] L. Popovic, "Determination of actual reduction factor of HV and MV cable lines passing through urban and suburban areas," *Facta universitatis - series: Electronics and Energetics*, vol. 27, no. 1, pp. 25–39, 2014, doi: 10.2298/fuee1401025p.
[15] L. M. Popović, "Ground fault current distribution when a ground fault occurs in HV substations located in an urban area," *Progress In Electromagnetics Research B*, no. 59, pp. 167–179, 2014, doi: 10.2528/PIERB14022004.
[16] L. M. Popović, "Transfer characteristics of electric-power lines passing through urban and suburban areas," *International Journal of Electrical Power and Energy Systems*, vol. 56, pp. 151–158, 2014, doi: 10.1016/j.ijepes.2013.11.011.
[17] Ljubivoje M. Popovic, "New Method for Determination of Inductive Influence of One or More Power Lines on Any Exposed Metal Installations," *International Journal of Engineering Research and Applications*, vol. 6, no. 1, pp. 36–46, 2016.
[18] I. Conductors and E. Society, "IEEE Guide for Bonding Shields and Sheaths of Single-Conductor Power Cables Rated 5 kV through 500 kV," 2014, doi: 10.1109/IEEESTD.2014.6905681.
[19] R. Benato, S. Sessa, F. Guglielmi, E. Partal, and N. Tleis, "Ground Return Current Behaviour in High Voltage Alternating Current Insulated Cables," *Energies*, vol. 7, no. 12, pp. 8116–8131, Dec. 2014, doi: 10.3390/en7128116.
[20] L. M. Popović, "Inductive influence of HV cable lines in urban and suburban areas," *Electric Power Systems Research*, vol. 176, 2019, doi: 10.1016/j.epsr.2019.105944.
[21] L. M. Popović, "Inductive influence of surrounding metal installations on power transfer capacity of HV cable lines with applied cross-bonding," *International Journal of Electrical Power and Energy Systems*, vol. 120, 2020, doi: 10.1016/j.ijepes.2020.105963.
[22] L. M. Popović, "Preliminary testing and assessment of safety conditions of HV substations located in urban areas," *Electric Power Systems Research*, vol. 195, 2021, doi: 10.1016/j.epsr.2021.107111.
[23] W. H. Kersting, *Distribution System Modeling and Analysis*. CRC Press, 2001.
[24] L. M. Popovic, *Relevant Characteristics of Power Lines Passing Through Urban Areas*, 1st Editio. Elsevier, 2022.
[25] L. M. Popović, "Comparative analysisof grounding systems formed by MV cable lines with either uninsulated or insulated metal sheath(s)," *Electric Power Systems Research*, vol. 81, no. 2, pp. 393–399, 2011, doi: 10.1016/j.epsr.2010.10.001.
[26] IEEE Std 80, *Standard 80-2000 Guide for Safety in AC substation gorunding*, vol. 56. 2000.

BIOGRAPHIE OF AUTHOR

Ljubivoje M. Popović was born in Markovac (at Mladenovac), Serbia, on Feb. 24, 1944. He received his BS, MS, and Ph.D. degrees in electrical engineering from the University of Belgrade in 1969, 1983, and 1991 respectively. In 1969 joined the Electric Power Distribution Company of Belgrade, where he stayed until retirement in 2007. In 1999 he was elected an associated professor at the School of Electrical Engineering, University of Beograd. Within about 40 years of research work, he has published more than 100 research papers as well as two scientific books under the following titles: "Actual Parameters of Power Limes Passing Through Urban Areas" and "Practical Methods for Analysis and Design of HV Installation Grounding Systemes". He can be contacted at email: ljubivoje@beotel.net.