

## New Method for Determination of Inductive Influence of One or More Power Lines on Any of Exposed Metal Installations

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### ABSTRACT

The paper presents the method solving the problem of inductive influence of high voltage power lines on nearby insulated metal installation in the cases when it appears in the urban surroundings, or when many relevant parameters are uncertain, or completely unknown. The problem appears as a consequence of the fact that many of surrounding urban installations are situated underground and cannot be visually determined or verified. The method developed here enables compensation of deficiency of all relevant, but unknown data. This has been done by determining the resulting screening factor involving the screening effects of all, known and unknown, surrounding metal installations in any concrete urban conditions. Also, the method enables determination of the relevant parameters of the equivalent screening conductor imagined around of the considered induction-affected installation and along the section of its exposition. The method is composed of the on-the site measurements and the calculation procedure based on the results of these measurements. The accuracy of the presented method has been verified by using a numerical example.

**Keywords** - induced voltage, screening effect, induced installation, return circuits, compensating conductor

### I. INTRODUCTION

The inductive influence of HV (high voltage) power lines on nearby insulated conductors (communication lines or different metal pipelines) has been subject of investigations for the last, five decades. This influence may be manifested in the way that represent a threat to the operating personnel and equipments, especially in the case of unbalanced operating conditions in the considered HV power network. Therefore, the problem requires to be considered in all, practically possible, environmental conditions and circumstances in order to prevent all, undesirable or harmful, consequences.

The increasing sizes of modern power 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.) closely spaced to HV distribution lines. Space dispositions of all of these installations, determined mainly by dispositions of city streets, and small mutual distances result in a strong inductive and, in the vicinity of substations, conductive coupling of the 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. The whole problem has three different aspects significant for current engineering practice. They, considered separately, can be defined as:

- influence of the surrounding metal installations on the fault current dissipated into the

surrounding earth through the grounding system of a supplied substation,

- influence of the surrounding metal installations on the transfer characteristics of power lines passing through urban and suburban areas, and
- influence of the surrounding metal installations on inductive influence of an HV power line on any of these installations considered separately.

The problem of determination of the influence of metal installations surrounding a feeding distribution line on ground fault current distribution through the grounding system of a supplied substation is solved in [1]. The solution is achieved by introducing one fictitious conductor of cylindrical form placed along and around the entire feeding cable-line. Somewhat later, this solution has been extended to include the overhead line as a feeding distribution line [2]. Then, the method for determination of the actual value of the ground fault current fraction that, in urban conditions, circulates only through the earth has been completed [3].

The investigation results presented in [1, 2] show that part of the ground fault current fraction flowing through the earth, in typically urban environments, is three to five times smaller than it has been considered earlier. This fact throws completely new light on the overall grounding problem of urban HV/MV distribution substations and dramatically changes our perception about the magnitude of this problem. It can now be seen, within a realistic framework, so that more economical solutions for this problem are now accessible.

The solution achieved in [1, 2] simultaneously gives possibility for solving another practical

problem that also has not been solved in the past. This is the problem of determination of the series-impedance parameters of distribution lines without ignoring the attendance of the surrounding metal installations. These installations act as additional neutral conductors of any distribution line passing through urban and suburban areas and, in accordance with this, improve its transfer characteristic. This, very useful influence depends on the types of the distribution lines (overhead or underground) and on the degree of urbanization of the area through which the lines pass [4].

The inductive influence of an HV line on an exposed metal installation can be estimated by using the current technical guide in this field [14, 15]. Also, many so far published papers propose different methodologies for solving this problem, relying mainly on Carson and Pollaczek formulae. The possibilities of different methods developed so far are separately considered in [6]. Some of them use computer software to achieve as accurate as possible simulation of the considered influence. For example, the method presented in [7] enables taking into account any number of pipelines, power lines, bonds, groundings, coating, and soil resistivity. Also, a rigorous solution for the electromagnetic field of underground conductors and a two-layer earth is presented in [11, 12]. The common characteristic of the current methods is that they enable taking into consideration the design/constructive characteristics and mutual space disposition of all conductors in the arrangement, as well as the characteristic of the surrounding earth as a conductive medium. However, none of them enables solution when problem appears in urban areas, or when many relevant data are uncertain or completely unknown.

This problem is solved in [5] by improving the method presented in [1, 2]. It has done by introducing into the calculation procedure an equivalent conductor that can be for the considered inducing line treated as an equivalent screening conductor. It substitutes, from the stand point of inductive effects, all surrounding metal installations including inducing line neutral conductor(s). By introducing this conductor, it is possible to determine the current induced in any of the surrounding metal installations seen separately, provided that its technical characteristics and space disposition with respect to the considered inducing line are known [5]. However, the screening factor (e. g. [14]) determined on the basis of this conductor represents an average screening factor which is exact only in the case when an induction-subjected installation is exposed along the whole inducing line length. Its value is not correct in the cases when the induction-subjected installation is exposed only along one section of the inducing line.

Without correct valuation of the local screening

factor [14] one remains without correct values of the voltages and currents that can appear in a planed metal installation that will be under the inductive influence. Since the ground fault current in an HV distribution network can be greater than 20 kA, it can mean that dangerous potential differences can appear without our knowledge and/or control at different public places. In the other words, the corresponding protective measures can be omitted in the cases where they are really indispensable. On the other hand, the protective measures can be applied in the cases where they are not necessary.

This problem is resolved here by determining the resulting screening factor substituting the inductive influences of all surrounding metal installations present within the section of exposure. The corresponding equivalent screening conductor is imagined as a cylinder situated around of the considered induced line and along the section of exposition.

The developed method is based on the self- and mutual impedances of line conductors installed in the semi-infinite and homogenous earth, e.g. [2]. It enables prediction of the voltages and currents induced in any metal installation planed in any concrete urban environment.

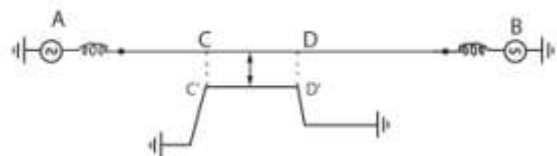
## II. BASIC PROBLEM DESCRIPTION

In rural areas due to strict environmental regulations, HV power lines and other types of metal installations are forced to share a common corridor called right-of-way and because of that these installations are very often mutually close. Also, in the case of urban and suburban areas such situations are practically unavoidable and HV power lines share the same streets with many different urban installations. As a final consequence of this, too high voltages can be induced in each metal installation located along and nearby an HV power line, particularly in the cases such as: long exposition and/or an unbalanced fault in the power system.

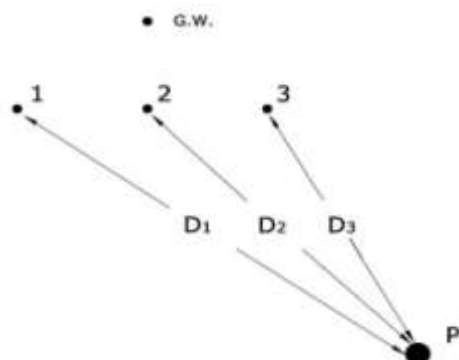
Under normal operating conditions, instead of a fraction of ground fault current, an unbalanced current circulates through the earth and neutral conductor(s), as well as all metal installations surrounding an HV feeding line [4]. Its value is certainly significantly smaller in comparison with the current appearing during a ground fault, but it flows permanently and because of that can be also dangerous, harmful and disturbing. 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. A close attention is required to determine inductances of circuit loops.

By disregarding for a while all others surrounding metal installations normally existing in

urban areas assume that an HV line having one section runs along the same street(s) as one planned metal installation. General case of their mutual inductive coupling is schematically presented as shown in Fig.1.



a. Mutual disposition of an HV line and an exposed installation



b. Geometrical data in the case of an HV overhead line

Fig. 1 Typical space disposition of one inducing line and one induced installation

The used notation has the following meaning:

C and D – end points on the inducing line that correspond to the end points of the exposed section of the induced installation,

C' and D' – end points of the exposed section of the induced installation,

R, S and T – phase conductors,

P – pipeline, or induced installation,

$D_1$ ,  $D_2$ , and  $D_3$  – distances/separations between the induced installation and each of the phase conductors, and

G.W. – ground wire or neutral conductor of the HV line.

The induced installation is insulated from earth all along its length and is earthed only at its ends. Then, grounding systems of a distribution HV/MV substation, A and B, located in urban areas consist 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 [10]. Thus, the spontaneously formed grounding system involves a large urban area around an HV/MV substation. This grounding system includes, through the terra-neutral (TN) grounding system in the low-voltage (LV) network and consumer installations, and many, known and unknown, metal installations typical for an urban

area. As a consequence, the outgoing MV cable lines simultaneously become the conductive connections with the metal installations laid along the same street(s) as the HV feeding line. Thus, it is not difficult to see that each unbalanced current appearing in an HV feeding line for its return into the power system uses earth as a conductive media and line neutral conductor(s) as well as many others available paths formed through the metal installations surrounding the HV feeding line. Thus, it can be said that this current is only partially returned through the grounding system of the supplied substation and earth, while the rest of this current returns through the line neutral conductor(s) and all metal installations surrounding the considered HV feeding line. Since the effective load currents of HV distribution lines are practically symmetrical in normal operation conditions, an unbalanced current appears only as a consequence of asymmetry in the phase conductor arrangement towards neutral conductor (s) and surrounding metal installations, Fig. 1.

As an illustration, the main current flows appearing during normal operation conditions within and around an HV distribution line are presented in Fig. 2.

On the basis of the given description, it is not difficult to see that all surrounding metal installations represent, in fact, the screening conductors. Thus, the whole problem can be formulated in a more direct way: How to determine the screening effects of all, known and unknown, surrounding metal installations?

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 [13], no one of them can be applicable in urban them conditions. The reason for this emanates from the fact that surfaces of urban areas are covered by buildings, streets, pavements, and many other permanently

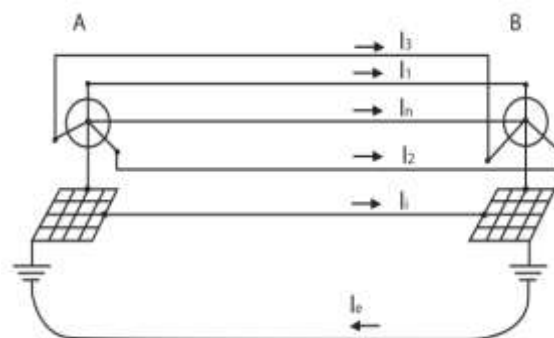


Fig. 2 Main current flows under normal operation conditions of an HV power line

The used notation has the following meaning:

A and B – substations at the ends of the HV distribution line,

$I_R, I_S, I_T$  – load currents flowing through the individual phase conductors,

$I_i$  – current induced in the metal installations surrounding the HV feeding line,

$I_n$  – current induced the line neutral conductor(s), and

$I_e$  – current injected into the earth through the grounding system of the supplied substation, B.

constructed objects; while under the ground surface many known and unknown metal installations are laid.

The main practical difficulty originates from the fact that the surrounding metal installations are mostly laid under the street pavements and many relevant data about them cannot be visually determined or verified. Because of that these data remain hidden and partly or completely unknown for the designers of a planned installation. It is only known that some of the surrounding metal installations are not in direct contact with the earth, while the others are in direct and continuous contact with earth. Then, it is known that their spatial dispositions and structures depend on many local factors and because of that they are different in each concrete case. Also, it is known that many of them are mutually connected. Therefore, they spontaneously form a very large and complex underground metal network whose structure and topology vary along any of the HV distribution lines. Because of that screening effect of the surrounding metal installations is different for different sections exposed to the same inducing line. Thus, it should be determined for each exposed section separately.

Each of the surrounding conductors, together with earth as the common return path, forms an electrical circuit, while all of them (line neutral conductor(s) and all surrounding metal installations) form inductively coupled electrical circuits, whose number is equal to the number of these conductors. Since these circuits can be represented by the corresponding system of equations and since the analytical expressions for the self and mutual impedances of these circuits are known (e.g. [4]), it can be said that the considered problem has been in principle solvable long time ago. However, it was not applicable because of many uncertain and unknown relevant data, including in some cases even the number of involved surrounding metal installations. Thus, the problem can be defined as follows: How to find the method providing the compensation of the lack of many relevant data?

### III. COMPLETE EQUIVALENT CIRCUIT

Let us consider separately inducing line and all surrounding metal installations acting as additional neutral conductors. Currents and voltages in phase

conductors of HV lines describe unbalanced or balanced power system in normal operation or under fault conditions. However, in the case of power lines passing through urban and/or suburban areas these currents induce in each of the surrounding metal installations certain electromotive force. Thus, each of these power lines represents in reality a very complex electrical circuit with many individual current flows. The number of these individual current flows, if the phase line conductors are excluded, is equal to the number of the line neutral conductors enlarged by the number of all surrounding metal installations. Also, the current induced in each of these individual surrounding conductors participates in creation the fluctuating magnetic field at each place around and along an HV distribution line.

With the aim of considering an, in reality spontaneously formed, electrical circuit of an HV line passing through urban and/or suburban areas, it is assumed that the HV line consists of three phase conductors and has three neutral conductors earthed at the line ends. Also, it is assumed that the total number of surrounding metal installations, including the line neutral conductors, is equal to an arbitrary number  $N$ . Finally, by taking into consideration that the currents through the phase conductors are known (e.g. obtained by measurements), on the basis of the former assumptions, this line can be represented by the equivalent circuit shown in Fig. 3.

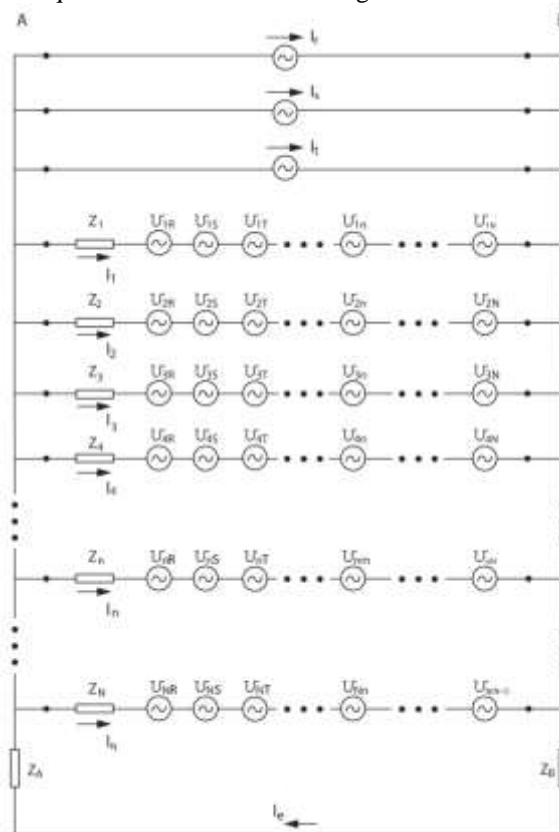


Fig. 3 Complete equivalent circuit of the line

The used notation has the following meaning:  
 $U_{nR}, U_{nS}, U_{nT}, \dots, U_{nN}$  - voltages induced in an arbitrary ( $n$ -th) circuit (metal installation) by the current in each of the surrounding conductors,  
 $I_R, I_S,$  and  $I_T$  - ideal current sources representing the currents in the line phase conductors,  
 $I_1, I_2, I_3$  - currents induced in the line neutral conductors,  
 $I_4, I_5, \dots, I_n, \dots, I_N$  - currents induced in the individual surrounding metal installations,  
 $Z_1, Z_2, Z_3$  - self-impedances of the line neutral conductors, and  
 $Z_4, Z_5, Z_6, \dots, Z_N$  - self-impedances of the individual surrounding metal installations.

As can be seen in the Fig. 3, the presented equivalent circuit is composed of the self and mutual impedances of the considered line conductors and all surrounding metal installations. The self impedance of an arbitrary,  $n^{\text{th}}$ , surrounding metal installation is, according to e.g. [4], determined by

$$Z'_n = R'_n + \omega \frac{\mu_0}{8} + j\omega \frac{\mu_0}{2\pi} \ln \frac{\delta}{r_n}; \quad \Omega/\text{km} \quad (1)$$

Mutual impedance between two arbitrary,  $n^{\text{th}}$  and  $m^{\text{th}}$ , surrounding metal installations is, according to e.g. [4], determined by

$$Z'_{mn} = \omega \frac{\mu_0}{8} + j\omega \frac{\mu_0}{2\pi} \ln \frac{\delta}{D}; \quad \Omega/\text{km} \quad (2)$$

where

$R'_n$  - per unit length resistance of an arbitrary,  $n^{\text{th}}$ , surrounding metal installation (conductor),  $\Omega/\text{km}$ ,  
 $r_n$  - medium radius of an arbitrary,  $n^{\text{th}}$ , surrounding metal installation (conductor) in meters, and  
 $D$  - distance between two arbitrary,  $n^{\text{th}}$  and  $m^{\text{th}}$ , surrounding metal installations (conductors) in meters.

The equivalent earth penetration depth  $\delta$  is determined by

$$\delta = 658 \sqrt{\frac{\rho}{f}}; \quad \text{m}, \quad (3)$$

where:

$\rho$  - equivalent soil resistivity in  $\Omega\text{m}$   
 $f$  - power frequency, or frequency of some higher harmonic.

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.

On the basis of the given circuit it is not difficult to see that each of the involved surrounding conductors cumulatively comprises the inductive influences of all other, known or unknown, surrounding metal installations (conductors). Also, current in an arbitrary surrounding conductor (Fig. 3),  $I_n$ , induces in an also arbitrary ( $m^{\text{th}}$ ) surrounding conductor a voltage,  $U_{mn}$ , which is, in general, determined by

$$U_{mn} = Z'_{mn} L_S I_n, \quad n \neq m \quad (4)$$

where

$L_S$  - length of the exposed section, km.

It is well known that distribution substations are located in areas occupied by many underground metal installations, acting as perfect grounding electrodes [10, 14]. Thus, relationships between the relevant parameters from the equivalent circuit of Fig. 3 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, it can be said that the current flows appearing in the line neutral conductor(s) and all others surrounding metal installations are a consequence solely of the mutual inductive influence of the currents in all surrounding conductors. Also, for further considerations it is necessary to mention that the current directions shown in Fig. 3 are taken arbitrarily.

In the case of a consideration of the inductive influence during ground fault conditions in an HV network, the presented equivalent circuit is somewhat different. Instead of three phase conductors, only the phase conductor carrying a ground fault current should be presented. Also, in the case of an overhead line the number of neutral conductors is usually only one.

On the basis of the equivalent circuit presented in Fig. 3, it is possible to write the system of  $N$  equations and, for the known the maximal value of the load currents ( $I_R, I_S,$  and  $I_T$ ) and all self- and mutual impedances, determine each of the current presented in the given equivalent circuit. Unfortunately, because of the previously mentioned practical difficulties, the number of surrounding metal installations and their parameters necessary for determination all self- and mutual impedances involved should be treated as unknown quantities. Thus, for solving the problem a completely new approach [5] was necessary. It is based on measuring test currents through the faulted phase conductor and through one of the neutral conductors (e.g.  $I_T$  and  $I_3$  in Fig. 3) and known mutual space disposition between the inducing conductor and the considered surrounding metal installation, as well as by substituting all others surrounding metal installations by only one equivalent conductor, imagined as a cylinder placed around and along the entire HV feeding line.

However, in the here considered problem the induced installation is exposed only to one section of the HV line, from C to D, as shown in Fig.1, while the surrounding metal installations actually existing along this section in general case are different in comparison with the metal installations surrounding inducing line along its whole length.

#### IV. INDUCTIVE INFLUENCE OF AN HV LINE

Data about the magnitude of actual inductive influence of a HV line are necessary already at the design stage of a planned/future nearby installation. The possibility for determining this influence is observed in the fact that, according to the equivalent circuit given in Fig. 3, the resulting voltage induced in each of the surrounding installations cumulatively involves the inductive influences of all surrounding metal installations. For the certain value(s) of the current(s) in the inducing line it depends on: local soil resistivity as well as the number and space positions of surrounding installations. Since all of these are unknown quantities in practical conditions, the resulting voltage that will be induced in the planned installation can be obtained only by the performing corresponding on-the-site measurements. However, at the design stage the planned installation does not exist. Thus, for the purpose of performing the necessary measurements instead of a planned installation one can use only one single-core cable. It would be utilized as a provisory cable line laid on the surface of the soil exactly along the foreseen section of parallelism, from C' to D', Fig. 1. For this purpose it is the best to use an LV single-core cable (with no metal sheath), suitable for application in different urban situations. This provisory cable line should be earthed at only one end with the aim of forming, together with the earth as the return path, an open electrical circuit. This electrical circuit is schematically presented in Fig. 4.

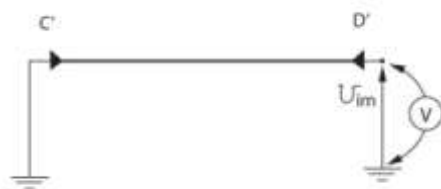


Fig. 4 Provisory electrical circuit necessary for on-the-site measurements

The used notation has the following meaning:  
 $U_{im}$  – total electro motive force induced in the provisory electrical circuit, and  
 $V$  – voltmeter.

Having in mind the equivalent circuit of a HV distribution line and surrounding metal installations,

presented in Fig. 3, the resulting voltage induced in the provisory cable line, if it is denoted as  $(N + 1)$ , is obtained from the following equations related to the unit section length:

- in the case of normal operating conditions
- 

$$U_{im} = Z_{(N+1)R} I_R + Z_{(N+1)S} I_S + Z_{(N+1)T} I_T + \sum_{n=1}^{n=N} Z_{(N+1)n} I_n \quad (5)$$

- in the case of the ground fault current passing through the nearest phase conductor T (critical case for the situation presented in Fig. 1)

$$U_{im}(I_f) = Z_{(N+1)T} I_f + \sum_{n=1}^{n=N} Z_{(N+1)n} I_n(I_f) \quad (6)$$

where:

$I_f$  – measured test current obtained by simulating the ground fault in the supplied substation B.

Since impedances:  $Z_{(N+1)R}$ ,  $Z_{(N+1)S}$  and  $Z_{(N+1)T}$  are known when the relevant data about the space position of the planned installation are known ( $D_1$ ,  $D_2$  and  $D_3$  in Fig. 1) and since the quantities:  $I_R$ ,  $I_S$ ,  $I_T$ ,  $I_f$  and  $U_{im}$  can be obtained by measurements, all these quantities can be treated as a priori known. Thus, according to (5), the resulting voltage induced under normal operation conditions by all, known and unknown, surrounding metal installations (screening conductors) can be obtained by

$$\sum_{n=1}^{n=N} Z_{(N+1)n} I_n = U_{im} - Z_{(N+1)R} I_R - Z_{(N+1)S} I_S - Z_{(N+1)T} I_T \quad (7)$$

Also, the resulting voltage which is under simulated ground-fault induced by all, known and unknown, surrounding metal installations can be obtained by

$$\sum_{n=1}^{n=N} Z_{(N+1)n} I_n(I_f) = U_{im} - Z_{(N+1)T} I_f \quad (8)$$

Magnitude of the screening effects is expressed as the amount of reduction of the value of the electrical quantity which is considered representative of the induction in the induced line due to the screening current(s) [14]. Thus, according to (5) and (6), the resulting screening factor is

- in the case of normal operating conditions

$$k = 1 + \frac{\sum_{n=1}^{n=N} Z_{(N+1)n} I_n}{Z_{(N+1)R} I_R + Z_{(N+1)S} I_S + Z_{(N+1)T} I_T} \quad (9)$$

- in the case of the test current,  $I_f$ , passing through the phase conductor T (Fig. 1)

$$k(I_f) = 1 + \frac{\sum_{n=1}^{n=N} Z_{(N+1)n} I_n(I_f)}{Z_{(N+1)T} I_f} \quad (10)$$

On the basis of (7) and (8) the expressions (9) and (10) obtain the following forms:

- in the case of normal operating conditions

$$k = \frac{U_{im}}{Z_{(N+1)R} I_R + Z_{(N+1)S} I_S + Z_{(N+1)T} I_T} \quad (11)$$

- in the case of the test current,  $I_f$ , passing through the phase conductor T (Fig. 1)

$$k(I_f) = \frac{U_{im}(I_f)}{Z_{(N+1)T} I_f} \quad (12)$$

In the case of a balanced three phase system, the induced electromotive force,  $U_i$ , is smaller compared to the longitudinal electromotive force generated by a ground fault current. Therefore, in the case of normal operating conditions it is sufficient to consider only exposure over a small separation (in general, several tens of m) [14].

The metal installations in urban areas are mainly under the soil surface and because of that the obtained resulting screening factor is slightly smaller than it will be in the case of an actual overhead line and slightly greater than it will be in the case of a cable line.

Since the actual ground fault current is significantly larger than the test current  $I_f$ , the actual voltage induced during a ground fault is

$$U_i(I_F) = k(I_f) I_F, \quad (13)$$

where

$I_F$  – actual ground fault current determined by separate study.

In accordance with the given expressions, once the value of the resulting local screening factor is determined, for determination of the voltages that will be induced in the planed installations under normal operating and fault line conditions, it is sufficient to calculate only the mutual impedance between this installation and the phase conductor(s) of the inducing line.

It is common practice to consider the induced electromotive force as the essential quantity caused by induction. When it is determined and when the self impedance of the planed installation and the grounding impedances/resistances at its ends (C' and D') are also determined, the current that will be induced in the planed installation can also be predicted.

Influence of the earth as a return conductor and influences of all surrounding metal installations, involved by the fluctuating magnetic field around and along the HV line, can be cumulatively expressed only through the value of the local screening factor  $k$ . Thus, when this parameter is known, the procedure of calculation/prediction of inductive influence in each concrete case can be reduced to the simplest case, when only one inducing and one screening conductor exist. However, in the cases when the predicted inductive influence is too high and the protective measures are mandatory, it can be necessary to determine the relevant parameters of this, equivalent screening conductor.

## V. EQUIVALENT SCREENING CONDUCTOR

If the predicted values of the voltage or current in certain case are considered too high, the measures for their mitigation are indispensable. Such measures are often in the form of a purposefully laid, so called compensating conductor. However, in an urban environment, the effects of this measure cannot be determined by any, so far known method. In accordance with Fig. 3, the problem originates from the fact that an additional metal installation means an additional equation for an incompletely defined system of equations.

With the aim of overcoming this problem let us imagine an equivalent conductor substituting, from the stand point of the screening effect, all actually existing surrounding metal installations. The problem of determination this conductor becomes solvable when it is assumed that this equivalent conductor is of cylindrical form and placed around the inducing line along entire its length [1-5]. In this case it is assumed that such conductor is placed around the planned installation and only along its section of exposure. Also, it is assumed that this conductor is perfectly grounded at its ends. Under these assumptions, the planed installation and its imagined screening conductor is schematically presented is shown in Fig. 5.

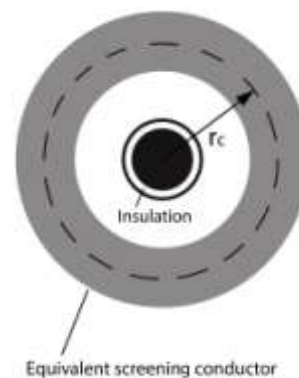


Fig. 5 Cross section of the planed installation and its equivalent screening conductor

On the basis of presented physical appearance of the imagined equivalent conductor, the corresponding equivalent circuit of one inducing conductor (e.g. phase conductor T with the current  $I_f$ ) and the formerly described provisory cable line becomes essentially simplified as shown in Fig. 6.

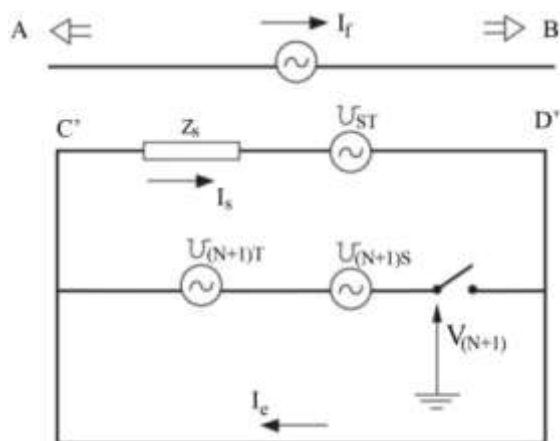


Fig. 6 The simplified equivalent circuit

The used notation has the following meaning:  
 $U_{(N+1)T}$  - voltage induced by current  $I_f$  in the provisory cable line,  
 $U_{(N+1)S}$  - voltage induced by current  $I_c$  in the provisory cable line,  
 $U_{ST}$  - voltage induced by current  $I_f$  in the equivalent conductor,  
 $I_s$  - current passing through the equivalent conductor,  
 $Z_s$  - self-impedance of the equivalent conductor.

Relevant parameters of the introduced equivalent conductor will be determined under condition that the voltage induced in the provisory cable line remains unchanged. On the basis the equivalent circuit presented in Fig. 6, this condition can be expressed by the following system of equations

$$\begin{aligned} 1. Z_{(N+1)T} I_f + Z_S I_S &= 0 \\ 2. Z_{(N+1)T} I_f + Z_{(N+1)S} I_S &= U_{im} \end{aligned} \quad (14)$$

where  
 $Z_s$  - self-impedance of the equivalent conductor,  
 $Z_{ST}$  - mutual impedance between the equivalent conductor and the phase conductor T, and  
 $U_{im}$  - measured value of the voltage induced in the provisory cable line, Fig. 5.

For the adopted physical appearance of the equivalent conductor, impedances  $Z_s$ ,  $Z_{(N+1)T}$  and  $Z_{(N+1)S}$  are a priori known and determined by

$$Z'_s = R'_s + \omega \frac{\mu_0}{8} + j\omega \frac{\mu_0}{2\pi} \ln \frac{\delta}{r_c}; \quad \Omega/\text{km} \quad (15)$$

$$Z'_{(N+1)S} = Z'_{ST} = \omega \frac{\mu_0}{8} + j\omega \frac{\mu_0}{2\pi} \ln \frac{\delta}{r_c}; \quad \Omega/\text{km} \quad (16)$$

where  
 $R'_s$  - per unit length resistance of the equivalent screening conductor,  $\Omega/\text{km}$ ,  
 $r_c$  - medium radius of the cylinder representing the equivalent screening conductor in meters.

Since voltage  $U_{im}$  is measured and impedances  $Z_{(N+1)T}$  and  $Z_{(N+1)S}$  can be determined by calculation, these quantities can be considered as known and the formerly defined condition can be expressed in the following, simpler mathematical form

$$\frac{Z_s}{Z_{(N+1)S}} = \frac{U_i}{U_i - U_{im}}, \quad (17)$$

where  
 $U_i$  - voltage which would have been induced, under the assumption, that the screening conductor(s) do not exist.

Since expression (17) gives the relationship between complex quantities, it can be presented as the following system of two equations

$$\begin{aligned} 1. \text{Re} \left\{ (U_i - U_{im}) Z'_s \right\} &= \text{Re} \left\{ U_i Z'_{(N+1)S} \right\}, \\ 2. \text{Im} \left\{ (U_i - U_{im}) Z'_s \right\} &= \text{Im} \left\{ U_i Z'_{(N+1)S} \right\} \end{aligned} \quad (18)$$

Then, the relevant parameters of the equivalent conductor ( $R'_s$  and  $r_c$ ), on the basis of equations: (10), (12), and (13), can be determined by

$$R'_s = \text{Re} \left\{ \frac{U_i}{U_i - U_{im}} Z_{(N+1)S} \right\} - \omega \frac{\mu_0}{8}, \quad (19)$$

$$X'_s = \text{Im} \left\{ \frac{U_i}{U_i - U_{im}} Z_{(N+1)S} \right\}, \quad (20)$$

$$r_c = \frac{\delta}{e^{2\pi X'_s / \omega \mu_0}}, \quad (21)$$

where  
 $R'_s$ ,  $X'_s$  - real and imaginary part of the self-impedance of the new equivalent conductor per kilometer,  $\Omega/\text{km}$ , and  
 $r_c$  - radius of the equivalent screening conductor in meters.

After determining the relevant parameters of the equivalent screening conductor ( $R'_s$  and  $r_c$ ), relations (15) and (16) can be used for obtaining:  $Z_s$ , and  $Z_{(N+1)S}$ , as well as:  $I_s$  and  $I_e$  (Fig. 6). Since the voltages:  $U_i$  and  $U_{im}$  represents the phasors for obtaining more accurate results it is necessary to



determine the phase angle between them. It can be done by measuring the phase angle between  $U_{im}$  and  $I_f$  and by corresponding calculation based on the equivalent circuit in Fig. 6.

When the relevant parameters of the equivalent screening conductor are known, by using analogous procedure and a priori defined space position of the compensating conductor (just behind the planned installation), one can determine the limiting value of the total impedance of the circuit formed by the compensation conductor. On the basis of this, one can adopt the conductor that should be installed to reduce the induced voltage within the prescribed limits and ensure the prescribed safety conditions or electromagnetic compatibility. Certainly, only determined on this way or by taking into account the favorable screening effects of all, known and unknown, surrounding metal installations this conductor can be adopted in accordance with the actual needs.

## VI. NUMERICAL VERIFICATION

### V.1 The necessary data and calculations

For this purpose let us assume one 110 kV distribution line consisting of three single-core XHLP cables laid in a triangular formation along the whole line length. The phase conductors of these cables are made of aluminum with a cross-section of  $1000 \text{ mm}^2$ , while their metal sheaths are made of copper strings with a total cross-section of  $95 \text{ mm}^2$ , and medium diameter is equal to 91 mm. Also, we will assume that the equivalent soil resistivity of the area through which this line passes is equal to  $30 \text{ } \Omega\text{m}$ .

Now, in order to verify the presented method let us assume that a ground fault current of 20 kA circulates through one of the line cables, while the metal sheath of one of other two cables is not grounded at one of the line ends. Also, it will be assumed that there are no other metal installations in the surrounding space. In accordance with these assumptions, this HV line can be presented by the equivalent circuit shown in Fig. 7.

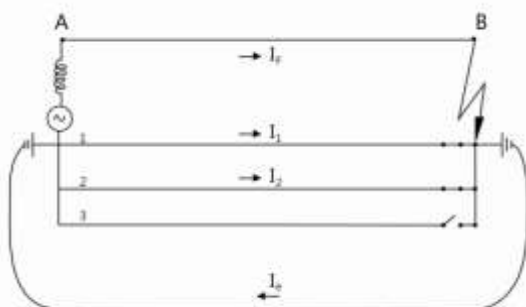


Fig. 7 Equivalent circuit of the assumed cable line

By using the existing method based on solving the system of equations (e.g. [9]) and the given equivalent circuit, it can be shown that the voltages

induced in the metal sheath with one end ungrounded have the following values:  $U_i = (986 + j10846) \text{ V/km}$  and  $U_{im} = (1735 + j276) \text{ V/km}$ . Then, by using these results as input data for the method presented here it can be obtained that the relevant parameters of the equivalent screening conductor substituting two grounded metal sheaths are:  $R'_C = 0.0936 \text{ } \Omega\text{/km}$ ,  $r_C = 66.1 \text{ mm}$ . Finally, on the basis of the given data it is not difficult to show that the resulting screening factor in the considered case is:  $k = (0.04377 + j0.16776)$ .

Since the same value for the induced voltage has been obtained by using the existing method based on solving the system of equations based on the given equivalent circuit (e.g. [9]), it can be said that the accuracy of the presented method has been verified.

### VI.2 Magnitude of the screening effects of surrounding metal installations

With the aim of obtaining certain insight into the quantity of possible screening effects of the surrounding metal installations in the formerly considered case, let us assume that the considered line is laid in an urban environment. The desired insight can be achieved on the basis of the results of the experimental investigations presented in [1-3]. These investigations performed on two 110 kV distribution lines of different lengths show that the relevant parameters of the equivalent conductor substituting all surrounding metal installations are the following:

- in the case of the line passing through the lower degree of urbanization:  $R'_C = 0.08 \text{ } \Omega\text{/km}$ ,  $r_C = 12.3 \text{ m}$ , and
- in the case of the line passing through the higher degree of urbanization:  $R'_C = 0.053 \text{ } \Omega\text{/km}$ ,  $r_C = 8.1 \text{ m}$ .

On the basis of these data, it is not difficult to show that the considered induced voltage is smaller by 16.8 % in the case of the lower and 61.4 % in the case of the higher degree of urbanization. This, certainly, leads to the general observations that the inductive influence of HV distribution lines depends of the degree of urbanization and that it is lower where the degree of urbanization is higher.

## VII. GENERAL CONSIDERATIONS

The presented analysis shows that the influences of many different, known and unknown, surrounding metal installations affecting the magnitude of the inductive influence of one or more HV lines in each concrete case can be completely represented by only one equivalent screening conductor. It is determined in each concrete case by on-the-site measurements and by the corresponding calculations. By determining this conductor, each practical situation, independent of its complexity and the number of known and unknown relevant parameters, becomes

easy solvable. From the mathematical point of view, it is interesting to be noted that this method offers solution in the cases, when, because of deficiency of relevant data, the solvable system of equations cannot be formed.

In accordance with expressions: (2), (19) and (21), the actual value of the equivalent soil resistivity is necessary for determination of  $Z_{(N+1)R}$ ,  $Z_{(N+1)S}$ ,  $Z_{(N+1)T}$ ,  $R_C$ , and  $r_C$ . However, although there are several methods of measurement of soil resistivity (e.g. [13]), none of them is applicable in urban conditions. The reason for this is due to the fact that the surfaces of urban areas are occupied by buildings, streets, pavements, and many other permanently constructed objects, while under the ground surface many known and unknown metal installations are present. 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 calculative part of the presented method. Here, the favorable circumstance is that the mentioned quantities are, according to the given analytical expressions, 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 safety side. Thus, it can be said that accuracy of the developed method depends practically only on the accuracy of the measurement of the voltage  $U_{im}$  and phase angle between this voltage and current(s) in the inducing line.

Since the presented method is based on the on site measurement data, it takes into account all relevant factors and parameters, including even those whose influence is very small. Some inaccuracy can appear only as a consequence of the inductive influence of the nearby distribution lines. If it is necessary, 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. [2-5]). The introduced error is small and gives the final results that are slightly on the safety side.

When the complex problem of inductive coupling appears in rural areas by application of this method the need for collection many relevant data and application of complicated calculations based on the possibilities of modern computers would be avoided. All necessary calculations can be implemented by using handheld calculators only.

With the full knowledge of the electromagnetic induction, utilities can acquire acceptable right-of way for their power lines, industries and commercial buildings can allocate their business at sufficient distances from the power lines, and utilities can

decide on the separation of their pipelines and railroads from power lines.

## VIII. CONCLUSION

The presented method enables obtaining solution of the problem of determining induced voltages due to electromagnetic fields of power lines passing through urban areas, or generally, when many relevant data are uncertain or completely unknown. The method takes into account all relevant factors and parameters in each practically possible environmental conditions. The problem solution is simplified without loss of accuracy by performing, here defined on-the-site measurements and applying a relatively simple, here developed, calculation procedure. The paper is also dealing with mitigation techniques to reduce the hazards of induction voltage. Finally, having in mind the simplicity and efficiency of the presented method, it could be used as a foundation for revision of the existing technical regulations in this field.

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