Proceedings of the Seventh IASTED International Conference
POWER AND ENERGY SYSTEMS
August 29–31, 2007, Palma de Mallorca, Spain
ISBN Hardcopy: 978-0-88986-689-8 / CD: 978-0-88986-690-4

GROUND FAULT CURRENT DISTRIBUTION IN SUBSTATIONS SUPPLIED BY NONUNIFORM MULTI-SECTION LINES

Stefano Mangione
Department of Electrical Engineering, University of Palermo
Viale delle Scienze – 90128 Palermo
Italy
mangione@diepa.unipa.it

ABSTRACT
The paper presents a general method for computing the distribution of substation ground fault current. The feeding line can be entirely homogeneous along its whole length or consisting of two or more different sections, i.e. part overhead and part underground cable. Based on the two-port theory, the proposed method allows to take into account all the relevant conductively and inductively coupled parameters which take part to the distribution of the fault current and can be easily implemented in a computer program. Numerical examples demonstrate the high efficiency of the proposed method.

KEY WORDS
Grounding, ground fault current, fault application transfer.

1. Introduction

When a fault to ground occurs in a substation, the fault current shares between the substation ground grid and several metallic additional return paths or other ground electrodes associated to the incoming and outgoing lines. In practice, a large portion of the fault current is diverted away from the faulted substation by the additional return paths associated to the incoming transmission lines, mutually coupled with the faulted phase conductor. Instead, a very small current is carried out by neutrals and return paths of outgoing lines, which only provide a ground impedance in parallel with the substation ground grid impedance [1]-[3].
The evaluation of the fraction of fault current emanating into the soil from the ground electrode of the faulted substation is then of prime importance, both for a more efficient and economic design of the substation ground system. This is almost treated by design engineers as a routine job in case of a substation supplied by an overhead line or an underground cable line, entirely homogeneous along the whole length [4]. The problem become extremely complicated when the substation is supplied by one or more transmission lines not homogeneous through their entire length, but consisting of two or more combined overhead-cable sections. Moreover, overhead lines may present different conductively and inductively coupled parameters along their length in case of non uniform ground wires.
In particular, in case of a combined overhead-cable feeding line, most of the ground fault current flows through the cable sheaths and discharges into the soil at the transition station (TS), where cables are connected to the overhead line [5]-[7]. This is due to the difference in coupling factors for cable and overhead lines, so that only a small quantity of the return current carried by cable sheaths continues toward the remote source through the overhead ground wire. On the contrary, a large portion of such a current flows into the soil surrounding the TS ground electrode and continues toward the remote source through the earth. This phenomenon, named “fault application transfer” [5], may cause shocks and equipment damages due to the TS ground potential rise (GPR). Then the evaluation of the fault current transferred to the TS structure and discharged locally into the soil is also of prime importance for safety concerns in its surrounding area.
Most of existing methods, which also consider non uniform feeding lines or overhead lines combined with cables, focus only on the estimation of the earth current and the related GPR at the fault location [8]-[9].
In this paper a new method to calculate the ground fault current distribution is presented. The feeding line can be entirely homogeneous along its whole length or consisting of two or more different sections, i.e. part overhead and part underground cable. The proposed method allows, besides the substation earth current calculation, also to determine the fault current discharged into the soil at the remote transition stations. Numerical applications demonstrate the high efficiency of the proposed method.

2. Overhead Line

In case of a phase-to-ground fault fed by an overhead line part of the fault current discharges into the soil through the ground grid of the faulted substation, part returns to the grounded neutral of remote source through the ground wire and towers ground electrode as shown in Fig. 1.

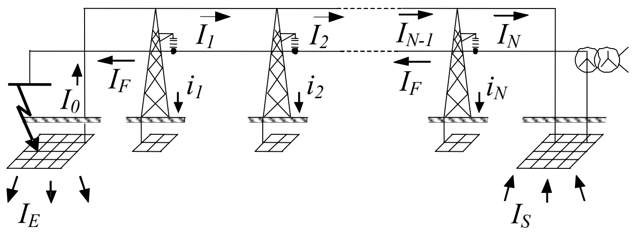

Fig. 1 - Ground fault at a substation fed by an overhead line.

With reference to the notation used in figure the following relationships hold:

$$I_E = I_F - I_0 \tag{1}$$

$$I_S = I_F - I_N \tag{2}$$

$$I_0 = \sum_{k=1}^{N} i_k + I_N \tag{3}$$

where N is the number of spans, I_F is the fault current, I_E and I_S are respectively earth currents discharged by the substation ground grid and collected by the ground electrode of the supply station, while I_0 indicates the fault current flowing through the first span of the overhead ground wire (return current).

2.1 Equivalent Ladder Circuit Model

If the ground wire is uniform along the whole line in number and characteristics and tower ground resistances and spans are assumed constant, the additional return path of the fault current through the ground wire and its ground connections through the towers electrode can be represented by a chain of as much identical Γ circuits as the number of line span is. As shown in Fig. 2 for three generic spans, each circuit consists of the ground wire self impedance Z_w, the tower footing resistance R_t and the emf induced by the fault current I_F upon the ground wire:

$$E_w = I_F\, Z_{cw} \tag{4}$$

being Z_{cw} the mutual impedance between the ground wire and the faulted conductor.

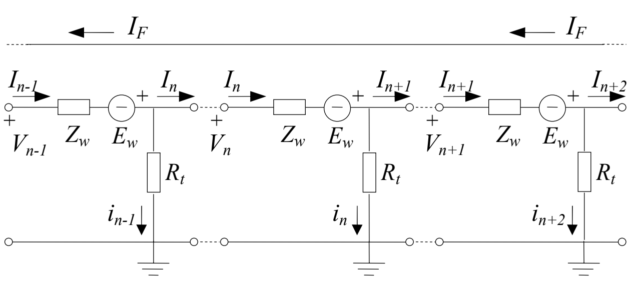

Fig. 2 – Equivalent scheme of three generic overhead line spans.

Both impedances Z_w and Z_{cw} are per span and for earth return and can be evaluated by means of Carson's theory, once the soil resistivity and the ground wire characteristics (number, material, size, spacing from phase conductors, etc…) are assigned.
The tower footing voltage and the ground wire current at the generic span n satisfy a set of finite-difference equations which solution is:

$$V_n = Ae^{-\gamma n} + Be^{\gamma n} \tag{5}$$

$$I_n = \frac{A}{Z'}e^{-\gamma n} - \frac{B}{Z''}e^{\gamma n} + \frac{E_w}{Z_w} \tag{6}$$

where Z' and Z'' are respectively the input and output equivalent impedances of the N quadrupoles chain and γ is the complex propagation constant.
The complex integration constants A and B can be obtained by imposing the boundary conditions given by (1) and (2). The current flowing through the first span of the ground wire can be obtained from (6) by setting $n=0$.

2.2 Equivalent Two-port Model

Referring to the two-port theory, the entire ladder circuit representing the overhead line, can be reduced to the compact equivalent two-port scheme in Fig. 3 containing at the input port the equivalent voltage generator K and the equivalent current generator H.
Input and output voltages and currents of the two-port scheme are related by the following matrix relationship:

$$\begin{bmatrix} V_N \\ I_N \end{bmatrix} = [b]\cdot\left[\begin{bmatrix} V_0 \\ I_0 \end{bmatrix} + \begin{bmatrix} K \\ H \end{bmatrix}\right] \tag{7}$$

in which $[b]$ is a matrix composed by the inverse transmission parameters b_{11} through b_{22}.

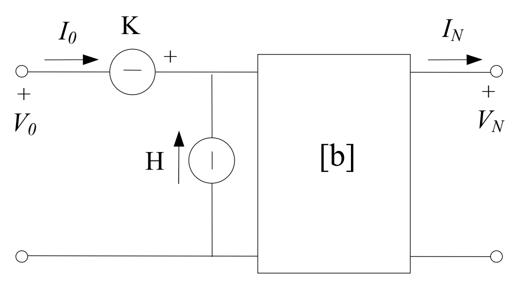

Fig. 3 – Equivalent two-port model.

If set $n=0$ in (5) and (6), constants A and B can be expressed in terms of V_0 and I_0 and, after some mathematical manipulations, by setting $n=N$ expressions (5) and (6) become as follows:

$$V_N = V_0\left(\cosh\gamma N - \frac{1}{T}\sinh\gamma N\right) - \frac{2I_0R_t\sinh\gamma N}{T} + \frac{2E_wR_t\sinh\gamma N}{Z_wT} \tag{8}$$

$$I_N = -\frac{2V_0}{Z_wT}\sinh\gamma N + I_0\left(\cosh\gamma N + \frac{1}{T}\sinh\gamma N\right) + \frac{E_w}{Z_w}\left(1 - \cosh\gamma N - \frac{1}{T}\sinh\gamma N\right) \tag{9}$$

where:

$$T = \sqrt{1 + \frac{4R_t}{Z_w}} \tag{10}$$

By comparing (8) and (9) with the algebraic equations derived from (7), the expressions for parameters of the equivalent two-port model can be found.

2.3 Non-uniform Overhead Line

Often the overhead transmission line is non-uniform along the whole length. It can consist of two or more sub-sections with the ground wire different in number and/or characteristics.
Such a situation arises when the line configuration changes, i.e. part with one ground wire and part with two ground wires, or if a better conducting ground wire is applied in a limited number of the line's receiving spans in order to reduce the earth current at the supplied station. In this case, a proper equivalent two-port model as that in Fig. 3 can be derived for each overhead line sub section.

3. Cable Line

Consider a phase-to-ground fault at a substation fed by an underground cable line consisting of three coated single-core cables transposed and with the metallic sheaths cross-bonded and grounded at both ends. The distribution of the fault current between the substation grounding grid and cable sheaths is schematically depicted in Fig. 4.

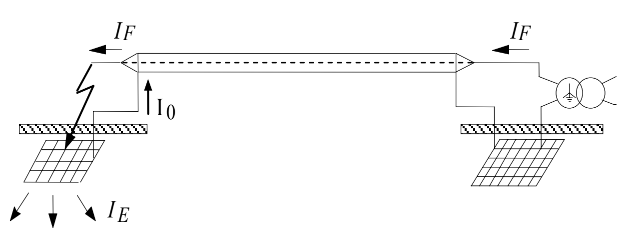

Fig. 4 – Single line diagram of a ground fault fed by a cable line.

With reference to the notation used in figure the following relation holds:

$$I_E = I_F - I_0 \tag{11}$$

where I_0 represents the total return current flowing through the cable sheaths.
The equivalent circuit of the cable line during the fault to ground is that in Fig. 5. The voltage source

$$E_s = I_F Z_{cs} \tag{12}$$

models the e.m.f. induced by the fault current upon the cable sheaths, due to their inductive coupling with phase conductors; being Z_{cs} the mutual impedances between cable sheaths and phase conductors and Z_s the self-impedance of the cable sheaths, all operating in parallel, with common earth return. Both impedances can be evaluated by means of Carson's theory, once soil resistivity and cable sheaths characteristics (material, size, cable spacing, etc…) are assigned.
It is assumed that the return current I_s divides equally between the three sheath circuits; this is undoubtedly truth with the cables in trefoil formation, but it can be assumed to be so also when the cables are laid flat with little error.

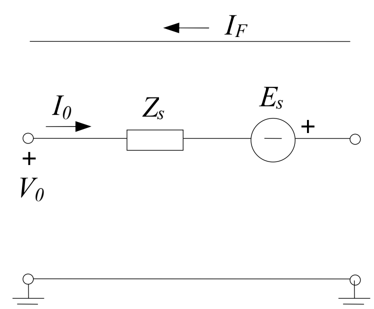

Fig. 5 – Equivalent circuit of a cable line.

3.1 Equivalent Two-port Model

If we want to represent the cable sheaths with the same equivalent two-port model of Fig. 3, the following relationships must be satisfied between input and output voltages and currents respectively:

$$V_N = V_0 - I_0Z_s + E_s \tag{13}$$

$$I_N = I_0 \tag{14}$$

Expressions for parameters of the equivalent two-port model in this case can be determined by comparing (8) and (9) with the algebraic equations derived from (7).

3.2 Cable Line with Intermediate Sheaths Grounding.

Besides both ends, often cable sheaths are grounded at each "major section" between three cross-bonding points, generally by grounding rods. In this case, assume the grounding rod resistance and the distance between two intermediate groundings constant along the entire line length and equal to the average values. The cable line can then be handled as an overhead line, as seen in section 2.1, and properly modelled by a chain of identical Γ circuits.

Expressions for parameters of the related equivalent two-port model can be determined by (8) and (9), in which R_t represents the resistance of grounding rods and Z_w and E_w are replaced respectively with Z_s and E_s.

4. Nonuniform Multi-Section Line

Consider now a combined multi-section overhead-cable line supplying a fault to ground at the substation A, as schematically represented in Fig. 6. The transformer secondary side of the supply station D is with solid grounded neutral. The overhead line may comprise two or more sub-sections, each sub section having the ground wire different in number and/or characteristics.

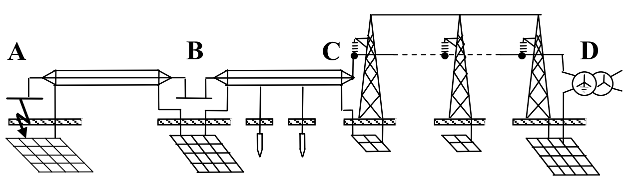

Fig. 6 – Ground fault fed by a non uniform multi-section line.

4.1 Transit/Transition Station

The ground return paths of the fault current at the transit station (B) or at the TS (C) can be also conveniently represented by the equivalent two-port model of Fig. 3.

To this end, consider the scheme of Fig. 7 in which R_T is the ground resistance of the transit/transition structure ground electrode. In order to define the parameters of the equivalent two-port model the following relationships must be satisfied between input and output voltages and currents:

$$V_N = V_0 \tag{15}$$

$$I_N = -\frac{V_0}{R_T} + I_0 \tag{16}$$

being

$$I_T = \frac{V_0}{R_T} \tag{17}$$

the earth current at the transit/transition station.

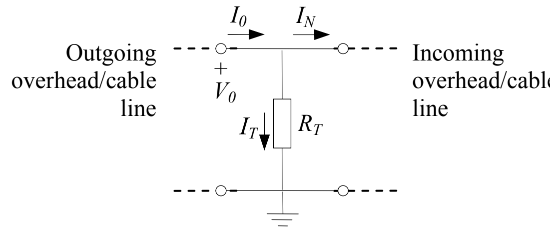

Fig. 7 – Equivalent scheme of a transit/transition station.

4.2 Compact Equivalent Two-port Line Model

By modelling with the proper two-port equivalent model each sub-section of the overhead line, each cable line section and each transit/transition station, the system in Fig. 6 can be represented by a cascade connection of M two-port blocks, in which outputs of each block are also inputs of the next block, as shown in Fig. 8 a). Referring to the two-port theory, the M two-port blocks then can be reduced to the compact equivalent model of Fig. 8 b), for which the following matrix relationship yields:

$$\begin{bmatrix} V_M \\ I_M \end{bmatrix} = \left[b_{M,1}\right] \cdot \left[\begin{bmatrix} V_0 \\ I_0 \end{bmatrix} + \begin{bmatrix} K^* \\ H^* \end{bmatrix} \right] \tag{18}$$

where

$$\begin{bmatrix} K^* \\ H^* \end{bmatrix} = \left[b_{M,1}\right]^{-1} \cdot \sum_{j=1}^{M} \left[b_{M,j}\right] \cdot \begin{bmatrix} K_j \\ H_j \end{bmatrix} \tag{19}$$

with

$$\left[b_{M,j}\right] = \left[b_M\right] \cdot \left[b_{M-1}\right] \cdot \left[b_{M-2}\right] \cdot \cdots \cdot \left[bj\right] \tag{20}$$

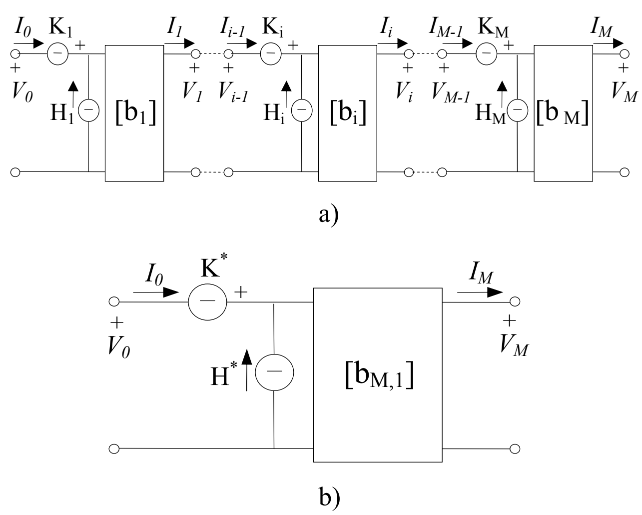

Fig. 8 – Two-port cascade (a) and compact equivalent model (b).

5. Problem Solution

From the above said, the calculation of ground fault current distribution between the substation ground grid and the additional ground return paths of whatever non uniform multi-section feeding line can be reduced to the solution of the simple circuit of Fig. 9, for which the following boundary equations yield:

$$I_0 = I_F - I_E = I_F - \frac{V_0}{R_E} \tag{21}$$

$$V_M = I_S R_S = (I_M - I_F) R_S \tag{22}$$

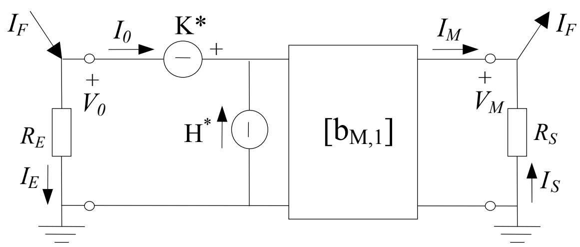

Fig. 9 – Two-port equivalent scheme for a uniform line section.

By solving the set of equations (21), (22) and (19), the input and output voltages and currents of the two-port scheme in Fig. 9 can be obtained and then the substation earth current can be determined simply as $I_E = V_0/R_E$.
Referring to the scheme of Fig. 8 a), from the knowledge of I_0 and V_0, by applying recursively the general two-port equation (7) the output voltage and current of each section can be obtained and also considered as inputs of the next section. In this way, being in mind (17), the earth current discharged at each transit/transition station can be also calculated.
In this manner critical situations due to the phenomenon of fault application transfer can be easily revealed at the design stage, in order to make the most suitable mitigation measures preventing hazards outside the fault location.

6. Application Examples

Consider a 110 kV multi-section overhead-cable line supplying a substation ground fault, as shown in Fig. 6. The underground cable sections A-B and B-C consist of a trefoil formation of coated single-core cables with a 50 mm^2 copper sheath. The geometric mean radius of cables sheath is 32.8 mm, while its resistance per unit length is 0.356 Ω/km. Both cable sections are considered 5 km long. At the base case we assume that the cable sheaths of line B-C are grounded along the route at every 350 m by grounding rods located at the cross-bonding points.

The overhead line section C-D is equipped, in a standard configuration, in one case with a single steel ground wire along the entire length and in the other case along the entire length save at several receiving-end spans, where an aluminium/steel ground wire is used. The resistances per unit length of steel and aluminium/steel ground wires respectively are 3.62 and 1.07 Ω/km and its geometric mean distance with phase conductors is 6.48 m. The length of spans is assumed 250 m and the towers' footing resistance 10 Ω (average values). The overhead line is considered 20 km long; in practice, its effect on the fault current distribution does not change with lengths of more than 15-20 spans.
Calculations are made assuming a realistic value of the ground fault current at the faulted substation of 10 kA, as known from prior system fault analysis.
The other relevant data are: specific soil resistance 50 Ωm; ground resistance in A 0.1 Ω, in B and D 0.5 Ω, in C 0.2 Ω.

6.1 Overhead Line with Uniform Ground Wire

At first we shall assume that the overhead line section is equipped by a steel ground wire along the entire length. The curves illustrated in Fig. 10 yield the earth currents dissipating into the soil at the faulted substation I_A, at the transit station I_B and at the transition station I_C, as a function of the grounding rod resistance of intermediate groundings along cable line B-C. The currents are expressed in per-unit absolute values of the total ground fault current.
As the grounding rod resistance increases, it can be observed that both the earth currents at the transit/transition stations increase considerably, while the variation of the earth current at the faulted substation is very small. In particular, if the cable section B-C is considered without intermediate groundings the following values (in p.u.) are obtained: I_A = 0.23, I_B = 0.28, I_C = 0.48; that is, the fault current transferred at the transition station should be more than twice the current discharged at the faulted substation.
In conclusion, from the viewpoint of safety the effect of intermediate grounding rods connected to cable sheaths along a cable line is well advantageous.

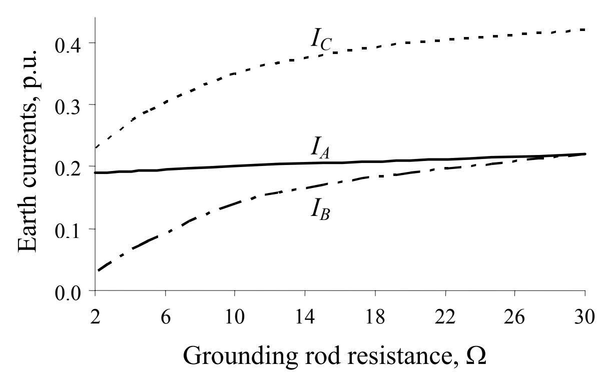

Fig. 10 – Earth currents in case of overhead steel ground wire.

6.2 Overhead Line with Non-uniform Ground Wire.

Now we shall assume that the overhead line section is equipped with a steel ground wire along the entire length save at 20 receiving-end spans, where an ACSR ground wire is used. In this case, the distribution of the faulted current between the faulted substation and the transit/transition stations is as shown in Fig. 11. As can be seen, by employing the better conducting ground wire the earth currents at the transit/transition stations (I_B and I_C) and at the faulted substation (I_A) decrease respectively up to 30% and 5%. In case of no intermediate groundings along the cable line B-C we obtain the following values: $I_A = 0.22$, $I_B = 0.20$, $I_C = 0.34$ (p.u.).

Note that in order to obtain similar effects on the earth currents reduction at both the transit/transition stations, it should be not necessary to apply the ACSR ground wire over the entire overhead line length; but it is sufficient to apply the better conducting ground wire in a maximum of 15-20 terminal spans.

6.3 Cable Lines Without Intermediate Grounding.

Fig. 12 shows the distribution of the faulted current between the faulted substation and the transit/transition stations as a function of the ground resistance at the TS, when the overhead line is equipped entirely with a steel ground wire and cable line B-C is supposed without intermediate groundings. As the TS ground resistance increases, it is evident that the fault current transferred at the transition station decreases. Nevertheless, note that high value of the TS ground resistance, and consequently lower values of I_C, does not imply better safety conditions in terms of local ground potentials. On the contrary, it can be demonstrated that the GPR at TS increases with the ground resistance.

7. Conclusion

Based on the two-port theory, a general method to calculate the distribution of the substation ground fault current has been presented. The feeding line can be entirely homogeneous along its whole length or consisting of two or more different sections.

The proposed method allows, besides the substation earth current calculation, also to determine the fault current discharged into the soil at remote transit/transition stations. Application example carried out by the computer implementation demonstrate the high efficiency of the method and provide some important insight about the effects of the fault application transfer phenomenon.

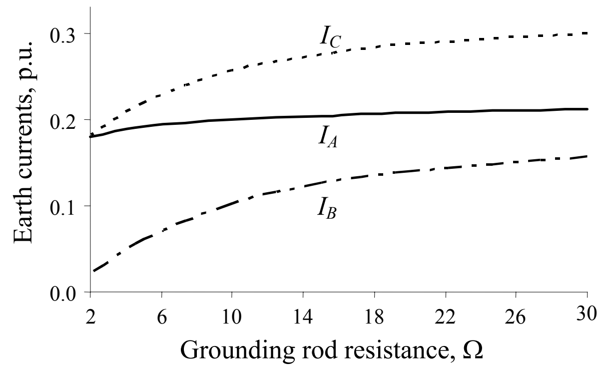

Fig. 11 – Earth currents in case of ACSR/Steel ground wire.

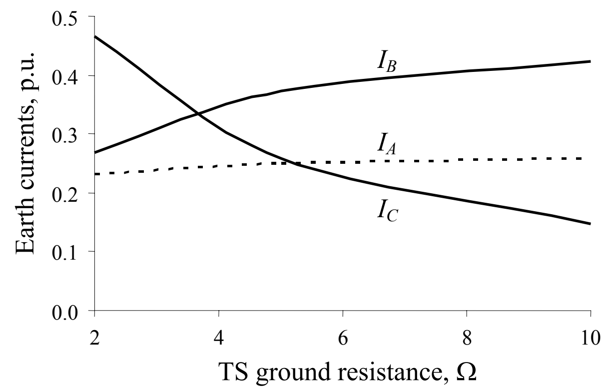

Fig. 12 – Earth currents in case of no intermediate groundings along cable lines route.

References

[1] D.L. Garret, J.G. Myers, S.G. Patel, Determination of maximum substation system fault current using graphical analysis, *IEEE Trans. Power Delivery*, *2*(3), 1987, 725-732.

[2] A.P. Meliopoulos, R.P. Webb, E.B. Joy, Computation of maximum earth current in substation switchyards, *IEEE Trans. Power Apparatus and Systems*, *102*(9), 1983, 3131-3139.

[3] J.M. Nahman, V.B. Djordjevic, D.D. Salamon, Grounding effects of HV and MV underground cables associated with urban distribution substation, *IEEE Trans. Power Delivery*, *17*(1), 2002, 111-116.

[4] IEEE Std 80-2000, *Guide for Safety in AC Substation Grounding* (New York, IEEE, 2000).

[5] S.T. Sobral, J.O. Barbosa, V.S. Costa, Ground potential rise characteristics of urban step-down substations fed by power cables – A practical example, *IEEE Trans. Power Delivery*, *3*(4), 1988, 1564-1572.

[6] J. Waes, M. Riet, F. Provoost, S. Cobben, Measurement of the current distribution near a substation during a single phase to ground fault, *CIRED 17th Int. Conf. on Electricity Distribution*, Barcellona, Spain, 2003.

[7] S. Mangione, Ground-fault current transfer at the transition station of a combined overhead-cable line - A parametric analysis, *POWERENG '07*, Setùbal, Portugal, 2007.

[8] L.M. Popovic, Practical method for evaluating Ground fault current distribution in station supplied by an unhomogeneous line, *IEEE Trans. Power Delivery*, *12*(2), 1997, 722-727.

[9] J. Nahman, Compact models of nonuniform lines for earthing-system analysis, *IEE Proc. Gener. Transm. Distrib.*, *148*(6), 2001, 579-582.