TRANSFERRED POTENTIAL FROM SUBSTATION HV/MV BY THREE-PHASE LINE COMPOSED OF THREE SINGLE-CORE CABLES

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Abstract: In this paper the grounding effects and transferred potential by three phase line composed of three single-core cables have been analyzed. The influence of the number of distribution substations, which the cable line supplies, as well as the resistivity of the earth electrode of these substations on the intensity of the transferred potential and on the value of the grounding impedance, which comprises the influence of the cable line and the distribution substations in calculating the grounding of feeding substation, has been considered.

INTRODUCTION

The medium-voltage single-core cables with crosslinked polyethylene insulation (e.g. cable types XHE 48, XHE 49) have been finding more application lately. The reason for this lies in the fact that the ampacity of these cables is larger than the ampacity of the paper insulated cables (i.e. cable types IPO 13, NPO 13), having in mind that the values of cross sections are the same. Since the single-core cables have polyethylene sheet the contact between the electrical screen and the soil in which the cable is buried has been prevented. Opposite of that, with the IPO cables, lead sheet and the armature come in contact with the ground, and the cable acts as a grounding electrode [1].
Therefore it is necessary to analyze the grounding characteristics of the three-phase medium-voltage lines composed of three single-core cables also. A line like these supplies several distribution substations (substation MV/LV) in which the electrical screens are connected to their earth electrodes. In that way the earth electrodes of distribution substations are connected, and it can be said that the line composed of single-core cables has certain grounding properties [1,2]. Considering that the electrical screens are also connected to the earth electrode of the feeding substation (substation HV/MV), during ground-fault in this substation the transferred potentials in the distribution substations are carried out. If the functional and the protective groundings are connected into the distribution substations, transferred potential can occur into the consumer installations.
Because of that, this paper analyzes the grounding effects and the potential transferred by three-phase line composed of three single-core cables. The influence of the number of distribution substations, which the line supplies, as well as the influence of grounding resistance of these substations on the intensity of the transferred potential are considered.

MATHEMATICAL MODEL

The mathematical model used for the analysis of the grounding effects and the transferred potentials is formed under following assumptions:

- the distances between neighbouring substations are equal (they are to be calculated using mean length, which is attained when the total line length is divided by the number of substations, which that line supplies),
- grounding impedances of substations are equal.

Taking into account these assumptions, the equivalent scheme shown in Fig. 1 can be formed. In Fig. 1. the impedance of the electrical screen between neighbouring substations is noted with $\underline{Z}_1$, while the grounding impedance is noted with $\underline{Z}_2$. Since the three-phase line is composed of three single-core cables, the impedance $\underline{Z}_1$ can be determined using the following relation [1,3,4]:

$$\underline{Z}_1 = \left(\frac{R_e}{3} + j\omega \frac{\mu_0}{2\pi} \ln \frac{D_{ek}}{\sqrt[3]{r_e a^2}} \right) \ell \quad , \tag{1}$$

where:

R_e - resistivity per unit length of the electrical screen of the cable,
ω - angular frequency of alternative current,
r_e -mean radius of electrical screen,
a - distance between the axes of two cables,
ℓ - mean distance between neighbouring substations,
D_{ek} - equivalent depth of earth return path.

The equivalent depth of earth return path depends on the frequency f and the soil resistivity ρ [1,3,4]:

$$D_{ek} = 658 \sqrt{\frac{\rho}{f}} \quad . \tag{2}$$

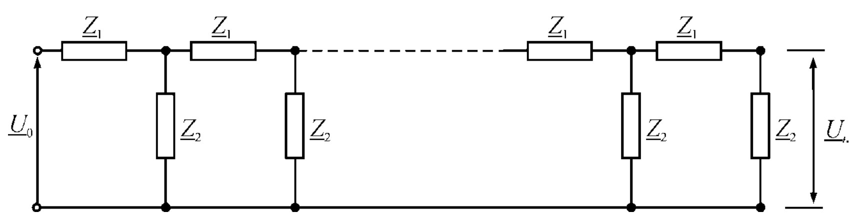

Fig. 1 Equivalent scheme used for the analysis of the grounding effects of XLPE cables

The scheme shown in Fig. 1 represents cascade connection of *n* inverse Γ-network models. For the sake of simpler mathematical analysis it is more convenient to transform the scheme shown in Fig. 1. into the scheme shown in Fig. 2. It can be seen that this scheme represents the cascade connection of symmetrical T-network models.

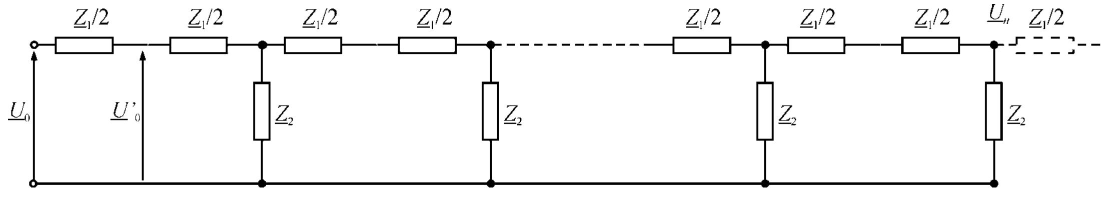

Fig. 2 Modified equivalent scheme from Fig. 1.

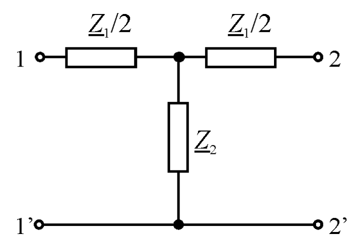

Fig. 3 Schematical description of symmetrical T-network

For one T two-port network, shown in Fig. 3, the following matrix relation can be written [2,5]:

$$\begin{bmatrix} \underline{U}_1 \\ \underline{I}_1 \end{bmatrix} = \begin{bmatrix} \underline{A} & \underline{B} \\ \underline{C} & \underline{D} \end{bmatrix} \begin{bmatrix} \underline{U}_2 \\ \underline{I}_2 \end{bmatrix} = [\underline{a}] \begin{bmatrix} \underline{U}_2 \\ \underline{I}_2 \end{bmatrix} \tag{3}$$

where:

$$\underline{A} = \underline{D} = 1 + \frac{\underline{Z}_1}{2\underline{Z}_2}, \qquad \underline{B} = \underline{Z}_1\left(1 + \frac{\underline{Z}_1}{4\underline{Z}_2}\right), \qquad \underline{C} = \frac{1}{\underline{Z}_2}. \tag{4}$$

The relation between the voltages and the currents at the input and the output of two-port network can be described by following equations:

$$\begin{aligned} \underline{U}_1 &= \underline{U}_2\, ch\underline{\gamma}_c + \underline{Z}_c \underline{I}_2\, sh\underline{\gamma}_c, \\ \underline{I}_1 &= \underline{U}_2 \frac{sh\underline{\gamma}_c}{\underline{Z}_c} + \underline{I}_2 ch\underline{\gamma}_c, \end{aligned} \tag{5}$$

where:

$$\underline{A} = \underline{D} = ch\underline{\gamma}_c, \qquad \underline{B} = \underline{Z}_c sh\underline{\gamma}_c, \qquad \underline{C} = \frac{sh\underline{\gamma}_c}{\underline{Z}_c} \quad . \tag{6}$$

In previously mentioned relations $\underline{Z}_c$ and $\underline{\gamma}_c$ are the characteristic impedance and the propagation coefficient, respectively:

$$\underline{Z}_C = \sqrt{\frac{\underline{B}}{\underline{C}}} \ ,$$

$$\underline{\gamma}_c = \ln(\underline{A} + \sqrt{\underline{B}\,\underline{C}}),$$

or:

$$\begin{aligned} \underline{Z}_C &= \sqrt{\underline{Z}_1 \underline{Z}_2 \left(1 + \frac{\underline{Z}_1}{4\underline{Z}_2}\right)} \quad , \\ \underline{\gamma}_c &= \ln\left[1 + \frac{\underline{Z}_1}{2\underline{Z}_2} + \sqrt{\frac{\underline{Z}_1}{\underline{Z}_2} + \left(\frac{\underline{Z}_1}{2\underline{Z}_2}\right)^2}\,\right] \ . \end{aligned} \tag{7}$$

For *n* identical symmetrical two-port networks connected into the cascade connection:

$$[\underline{a}] = [\underline{a}_1][\underline{a}_2][\underline{a}_3]..[\underline{a}_n] = \begin{bmatrix} ch(n\underline{\gamma}_c) & \underline{Z}_c sh(n\underline{\gamma}_c) \\ \frac{sh(n\underline{\gamma}_c)}{\underline{Z}_c} & ch(n\underline{\gamma}_c) \end{bmatrix} \tag{8}$$

Relation (8) shows that the $\underline{\gamma}_c$ coefficient of *n* identical symmetrical two-port networks connected into the cascade is *n* times larger than the coefficient of a single two-port network. The characteristic impedance of the entire cascade is equal to the characteristic impedance of a single two-port network. Having in mind the numeration in Fig. 2, and taking into account the fact that the current at the end of a modified equivalent scheme $\underline{I}_n = 0$, it follows:

$$\begin{aligned} \underline{U}'_0 &= \underline{U}_n\, ch(n\underline{\gamma}_c)\ , \\ \underline{I}'_0 &= \underline{U}_n \frac{sh(n\underline{\gamma}_c)}{\underline{Z}_c}\ , \end{aligned} \tag{9}$$

or:

$$\begin{aligned} \underline{U}_0 &= \underline{U}'_0 + \frac{\underline{Z}_1}{2}\underline{I}_0 = \underline{U}_n\, ch(n\underline{\gamma}_c) + \frac{\underline{Z}_1}{2}\underline{I}_0\ , \\ \underline{I}_0 &= \underline{I}'_0\ . \end{aligned} \tag{10}$$

Finally, the relation between the voltages at the beginning of the electrical screens of cables (the voltage at the earth electrode of feeding substation) and at the end of electrical screens (the voltage at the earth electrode of the *n*-th distribution substation) is:

$$\underline{U}_0 = \underline{U}_n \left(ch(n\underline{\gamma}_c) + \frac{\underline{Z}_1}{2\underline{Z}_c} sh(n\underline{\gamma}_c) \right)\ . \tag{11}$$

The voltage at the earth electrode of *k*-th distribution substation, starting from the feeding end of the cable, can be determined taking into account equation (9). Considering that between *k*-th and the last *n*-th substation there are (*n*-*k*) substations, the voltage and the current of the output of the *k*-th T two-port network is:

$$\begin{aligned} \underline{U}'_k &= \underline{U}_n\, ch\big((n-k)\,\underline{\gamma}_c\big)\,, \\ \underline{I}'_k &= \underline{U}_n \frac{sh\big((n-k)\,\underline{\gamma}_c\big)}{\underline{Z}_c}\ , \end{aligned} \tag{12}$$

For the voltage at the ground electrode of the *k*-th substation we attain:

$$\underline{U}_k = \underline{U}'_k + \frac{\underline{Z}_1}{2}\underline{I}'_k\ , \tag{13}$$

or:

$$\underline{U}_k = \underline{U}_n \left(ch\big((n-k)\,\underline{\gamma}_c\big) + \frac{\underline{Z}_1}{2\underline{Z}_c} sh\big((n-k)\,\underline{\gamma}_c\big) \right)\ . \tag{14}$$

Dividing the voltage $\underline{U}_k$ with the voltage at the beginning of the line $\underline{U}_0$, the coefficient of transferred potential $\underline{K}_i(k)$ for the given substation is attained.

$$\underline{K}_i(k)=\frac{\underline{U}_k}{\underline{U}_0}\ ,\quad k=1,2,\cdots,n\ . \tag{15}$$

Taking into account the relations (11) and (14) for the modulus of transferred potential we obtain:

$$K_i(k)=\left|\frac{ch((n-k)\underline{\gamma}_c)+\dfrac{\underline{Z}_1}{2\underline{Z}_c}sh((n-k)\underline{\gamma}_c)}{ch(n\underline{\gamma}_c)+\dfrac{\underline{Z}_1}{2\underline{Z}_c}sh(n\underline{\gamma}_c)}\right|,\quad k=1,2,\cdots,n\ . \tag{16}$$

Using the relations for the voltage and the current at the beginning of the cable line, the ground impedance is easily determined, which comprises the influence of the cable line and the substations, which that line supplies, when the earthing of the feeding substation HV/MV is calculated.

$$\underline{Z}_u=\frac{\underline{U}_0}{\underline{I}_0}=\underline{Z}_c\frac{ch(n\underline{\gamma}_c)}{sh(n\underline{\gamma}_c)}+\frac{\underline{Z}_1}{2}\ . \tag{17}$$

Besides the T-network models, the Π ones can also be used. In that case, the modulus of the transferred potential is:

$$K_i(k)=\left|\frac{ch((n-k)\underline{\gamma}_c)+\dfrac{\underline{Z}_{c\Pi}}{2\underline{Z}_2}sh((n-k)\underline{\gamma}_c)}{\left(1+\dfrac{\underline{Z}_1}{\underline{Z}_2}\right)ch((n-1)\underline{\gamma}_c)+\left(\dfrac{\underline{Z}_1}{\underline{Z}_{c\Pi}}+\dfrac{\underline{Z}_{c\Pi}}{2\underline{Z}_2}+\dfrac{\underline{Z}_1\underline{Z}_{c\Pi}}{2\underline{Z}_2^2}\right)sh((n-1)\underline{\gamma}_c)}\right|,\quad k=1,2,\cdots,n\ . \tag{18}$$

where:

$$\underline{Z}_{c\Pi}=\sqrt{\frac{\underline{Z}_1\underline{Z}_2}{1+\dfrac{\underline{Z}_1}{4\underline{Z}_2}}}\ . \tag{19}$$

Using Π -network models, the impedance $\underline{Z}_u$ is:

$$\underline{Z}_u=\underline{Z}_1+\frac{2\underline{Z}_2\underline{Z}'_u}{2\underline{Z}_2+\underline{Z}'_u}\ , \tag{20}$$

where:

$$\underline{Z}'_u=\underline{Z}_{c\Pi}\frac{ch((n-1)\underline{\gamma}_c)+\dfrac{\underline{Z}_{c\Pi}}{2\underline{Z}_2}sh((n-1)\underline{\gamma}_c)}{sh((n-1)\underline{\gamma}_c)+\dfrac{\underline{Z}_{c\Pi}}{2\underline{Z}_2}ch((n-1)\underline{\gamma}_c)}\ . \tag{21}$$

Analyzing relations (18) and (20), it can be shown that they are equivalent to the relations (16) and (17).

RESULTS OF CALCULATION

The presented method is used to analyze potentials transferred by three-phase 10 kV line composed of three single-core cables XHE 49, with the conductor cross section area of 120 mm^2. The cross section area of electrical screen of these cables is 16 mm^2, and the outer diameter of cables is 29 mm. The cables lie in a trefoil arrangement. Assuming $\rho = 50\ \Omega\mathrm{m}$ for the specific electrical resistivity of the soil, the value of impedance $\underline{Z}_1$ per unit length is $\underline{z}_1 = 0.38 + j0.65\ \Omega/\mathrm{km}$. The distances between neighbouring distribution substations are varied in analyses, as well as the impedances of substation ground electrodes. The number of distribution substations is also varied in the range of 1 to 8.

Figures 4, 5, and 6 show dependence of the modulus of the coefficient of the transferred potential when the mean distance between the neighbouring substations is $\ell = 0.5\ \mathrm{km}$, and the values of the ground impedance of the distribution substations $\underline{Z}_2$ is 1 Ω, 3 Ω and 5 Ω, respectively. The values of the earthing electrodes resistivities are suggested in paper [6] and with them are comprised the earthing electrodes in the city areas (of lesser resistivity) and in the rural (of larger resistivity) regions, also. In the Figures the parameter *n* represents the total number of substations, which the cable line supplies. It is clear that the largest value of the transferred potential is on the earth electrode of the first substation that is the one nearest to the feeding substation. The largest value of the transferred potential on the earth electrode of the first substation will be if that is also the only substation, which that cable line supplies. By increasing the number of substations, which the line supplies, a significant decrease in the value of the transferred potential of the first substation occurs. Besides that, from Figures 4, 5, and 6 it can be concluded that with the increase of the earth electrode resistance of the substation, the increase of the transferred potential appears.

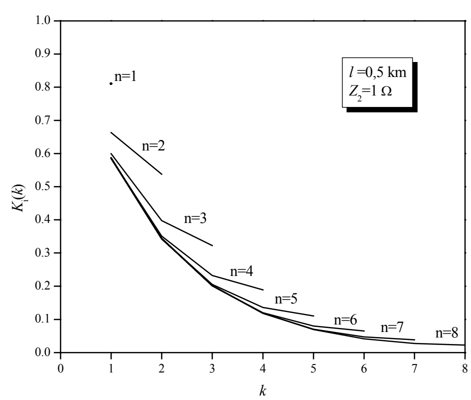

Fig. 4. The dependence of the modulus of the transferred potential coefficient for $\ell = 0.5\ \mathrm{km}$ and $\underline{Z}_2 = 1\ \Omega$

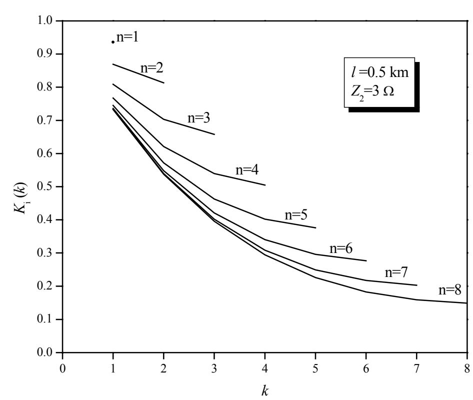

Fig. 5. The dependence of the modulus of the transferred potential coefficient for $\ell = 0.5\ \mathrm{km}$ and $\underline{Z}_2 = 3\ \Omega$

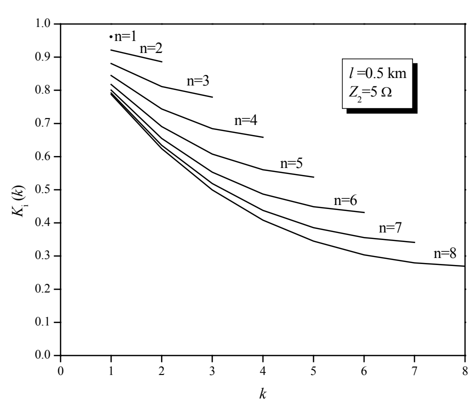

Fig. 6. The dependence of the modulus of the transferred potential coefficient for $\ell = 0.5\ \mathrm{km}$ and $\underline{Z}_2 = 5\ \Omega$

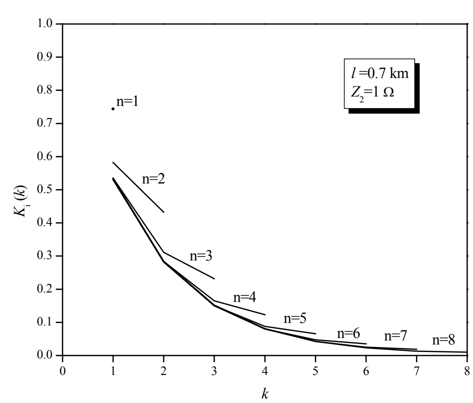

Fig. 7. The dependence of the modulus of the transferred potential coefficient for $\ell = 0.5\ \mathrm{km}$ and $\underline{Z}_2 = 1\ \Omega$

In order to see how the mean distance affects the value of the transferred potential, on Figures 7, 8 and 9 the dependence of the transferred potential coefficient for $\ell = 0.7\ \mathrm{km}$ and the values of earth electrode impedances $\underline{Z}_2$ of 1 Ω, 3 Ω and 5 Ω, respectively is shown. Comparing these Figures with the Figures 4, 5 and 6 it can be concluded that the increase of the distance between neighbouring substations leads to the decrease of the value of the coefficient K_i, i.e. the decrease of the transferred potential.

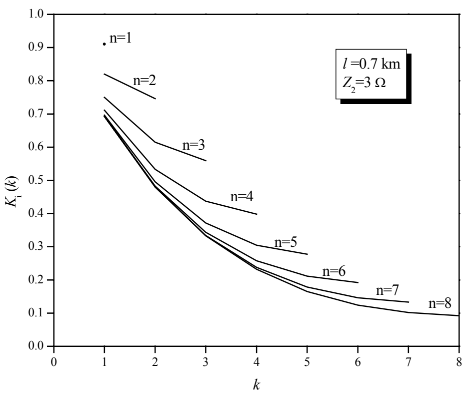

Fig. 8. The dependence of the modulus of the transferred potential coefficient for $\ell = 0.7\ \mathrm{km}$ and $\underline{Z}_2 = 3\,\Omega$

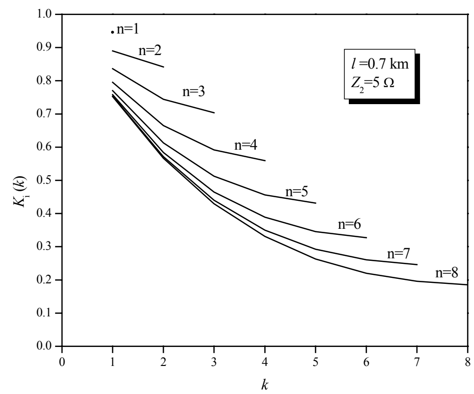

Fig. 9. The dependence of the modulus of the transferred potential coefficient for $\ell = 0.7\ \mathrm{km}$ and $\underline{Z}_2 = 5\,\Omega$

In certain cities, due to the larger load density, small distances between the neighbouring substations can be found. Therefore, in Figures 10 and 11 the dependences of the modulus of the transferred potential coefficient for $\ell = 0.3$ km and $\ell = 0.1$ km and $\underline{Z}_2 = 1\,\Omega$ are shown. These Figures show that when there is a small distance between neighbouring substations and a small number of substations supplied by the cable line, the value of the transferred potential on the earthing electrode of the first substation can be considerably large.

Analyzing the characteristics shown in previous Figures it can be concluded that the value of the transferred potential depends on the number substations supplied by the cable line and on the modulus of the ratio of the impedances $\underline{Z}_1$ and $\underline{Z}_2$. If the value $|\underline{Z}_1 / \underline{Z}_2|$ is larger, the value of the transferred potential is that much lower. This can be explained with the fact that in the case of larger values of the impedance $\underline{Z}_1$ the larger voltage drops on electrical screens are present, which stipulates the lower potentials on the earth electrodes of substations.

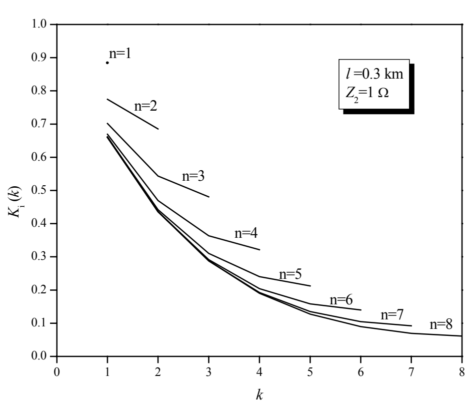

Fig.10. The dependence of the modulus of the transferred potential coefficient for $\ell = 0.3\ \mathrm{km}$ and $\underline{Z}_2 = 1\,\Omega$

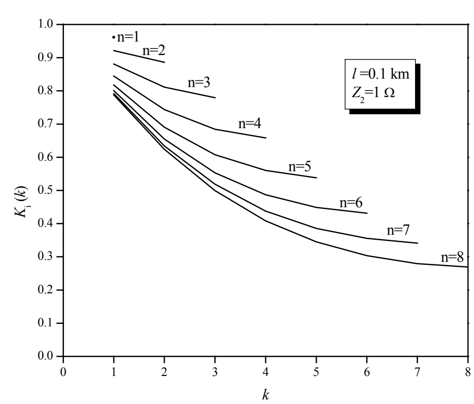

Fig.11. The dependence of the modulus of the transferred potential coefficient for $\ell = 0.1\ \mathrm{km}$ and $\underline{Z}_2 = 1\,\Omega$

In Figures 12 and 13 the dependence of the modulus of the impedance Z_u, which comprises the influence of the cable line while calculating the earth electrode of substations is shown. It is clear that with the increase of the impedance $\underline{Z}_1$, or $\underline{Z}_2$, the value of impedance Z_u rises. Still, from Fig. 12 it can be seen that the value of impedance Z_u reaches steady value, which can theoretically be attained for $n \to \infty$, when there are two or three substations on the line. In the cases when the value of the impedance $\underline{Z}_2$ is larger, several substations are necessary to be connected to the line for the steady value of the impedance Z_u to be achieved (Fig. 13). Here can also be said that the steady value of the impedance Z_u is reached with a smaller number of substations connected to the line if the value of $|\underline{Z}_1 / \underline{Z}_2|$ is larger.

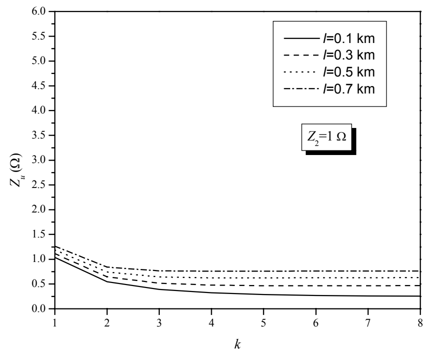

Fig. 12 The dependence of the modulus of input impedance for $\underline{Z}_2 = 1\,\Omega$

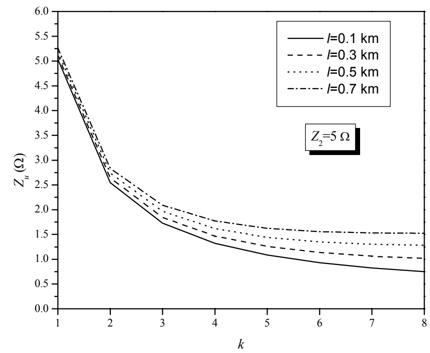

Fig. 13 The dependence of the modulus of input impedance for $\underline{Z}_2 = 5\,\Omega$

CONCLUSION

The value of the transferred potential is largest on the earth electrode of the first substation, that is the substation, which is nearest to the feeding substation. From the view of the transferred potential, the worst case is when that is only substation supplied by the cable line. This conclusion has a theoretical significance, because this case is rarely met in praxis. By increasing the number of substations supplied by the line a significant decrease of the value of the transferred potential on the earth electrode of the first substation occurs.

The value of the transferred potential depends on the number of substations supplied by the cable line and on the modulus of the ratio of impedances $\underline{Z}_1$ and $\underline{Z}_2$. If the value $|\underline{Z}_1 / \underline{Z}_2|$ is larger, the value of the transferred potential is that much lower.

In the cases when the first distribution substation is quite near to the feeding substation or when there is a large difference in the distances between neighbouring substations, there is a detailed calculation to be made, from the aspect of the transferred potential.

The steady value of the earth electrode impedance Z_u, which comprises the influence of the cable line in calculation of the earth electrode of the feeding substation, is achieved with a smaller number of substations connected to the line if the value $|\underline{Z}_1 / \underline{Z}_2|$ is larger.

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