ODREĐIVANJE MATRICE KOEFICIJENATA REDUKCIJE SUSTAVA KABELSKIH VODOVA

DETERMINATION OF THE POWER CABLES SYSTEM REDUCTION COEFFICIENT MATRIX

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U radu su prezentirane izvorne teorijske podloge matematičkog modela za određivanje matrice koeficijenata redukcije sustava kabelskih vodova. Riječ je o novom i posve općenitom matematičkom modelu koji može uvažiti proizvoljan broj i raspored sustava jednožilnih kabela složenih u trokutnom snopu. Dotična matrica koeficijenata redukcije uračunava, naime, stvarni (potpuni) elektromagnetski utjecaj koji vlada među pripadnim kabelskim vodovima, u uvjetima nastupa jednopolnoga kratkog spoja. Za matricu koeficijenata redukcije značajno je da njeni elementi ovise isključivo o elektromagnetskim i geometrijskim značajkama samih kabelskih vodova, o njihovom smještaju te o geofizikalnim svojstvima njihove trase, kao i o frekvenciji struja koje teku kabelskim vodovima. Primjena ovdje razvijenog modela omogućava daleko točniji proračun raspodjele struja u sustavu kabelskih vodova nego li je to moguće primjenom pojedinačnih faktora redukcije nazočnih kabelskih vodova. Istodobno, razvijeni model je jednostavan za primjenu i posve općenit. Primjena prezentirane teorije i razvijenog matematičkog modela prikazana je i na primjeru općeg sustava kabelskih vodova nazivnog napona 110 kV.

The work presents original theoretical bases of the mathematical model for the determination of the power cables system reduction coefficient matrix. The matter at hand is a new and completely general mathematical model which can take into consideration an arbitrary number and arrangement of a single-core cable system arranged in a treefoil formation. As a matter of fact, the concerned reduction coefficient matrix takes into consideration the real (full) electromagnetic impact which dominates the pertaining power cables, in the conditions of occurrence of one-pole short circuit. The reduction coefficient matrix is characterized by having elements dependant exclusively on electromagnetic and geometrical properties of the very power cables, their positioning and on the geophysical properties of their route, as well as on the frequency of the currents flowing through the power cables. The application of the model deliberated here enables a far more accurate estimation of the current distribution in the power cables system than would be possible by applying separate reduction factors of the present power cables. At the same time, the deliberated model is simple for application and entirely general. The application of the presented theory and the developed mathematical model is also shown on the example of the general system of power cables with nominal voltage 110 kV.

Ključne riječi: elektromagnetska sprega; jednopolni kratki spoj; koeficijent redukcije; matrica; sustav kabelskih vodova
Key words: electromagnetic coupling; matrix; one-pole short circuit; power cables system; reduction coefficient

Sarajčev, P., Određivanje matrice koeficijenata redukcije sustava kabelskih vodova, Energija, god. 58(2009), br. 3., str. 308-323
Sarajčev, P., Determination of the Power Cables System Reduction Coefficient Matrix, Energija vol. 58(2009), No. 3, pp. 308-323
https://doi.org/10.37798/2009583303

1 UVOD

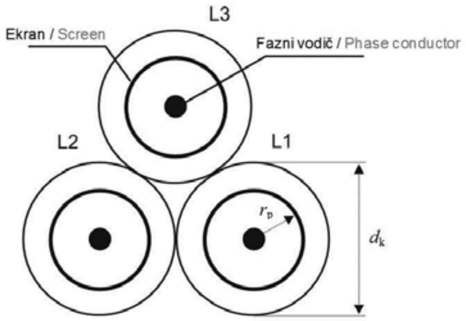
Razvitak većih urbanih područja i porast potrošnje električne energije u njima zahtijevaju primjenu kabelskih vodova sve viših nazivnih napona. Radi se redovito o sustavima kabelskih vodova koji dijelom ili u cijelosti imaju zajedničke kabelske trase. Ovi kabelski vodovi izvode se danas gotovo isključivo od jednožilnih kabela, s krutom izolacijom (umreženi polietilen – XLPE). Ovi kabeli sastoje se od faznog vodiča, koji se izrađuje od bakra ili aluminija, metalnog ekrana te poluvodljivih slojeva ispod i iznad izolacije. Osim toga, iznad ekrana oni u pravilu imaju bubrivu vrpcu i aluminijski laminat, za uzdužno i poprečno zapiranje prodora vlage. Naime, izolacija od umreženog polietilena je veoma osjetljiva na utjecaj vlage (nastup tzv. vodenih grančica). Konačno slijedi vanjski plašt jednožilnog kabela, koji se često izvodi od HDPE (polietilen velike gustoće), [1].

Kabelski vod se sastoji od tri spomenuta jednožilna kebala, koji se najčešće polažu u trokutnom snopu i pritom se međusobno dotiču. Njihov poprečni presjek grafički je ilustriran na slici 1.

1 INTRODUCTION

The development of larger urban areas and increased consumption of electricity in those areas require the application of power cables of increasingly higher nominal voltages. Those are regularly power cables systems which have common cable routes partly or in full. Today, these power cables are constructed almost exclusively of single-core cables with solid insulation (cross-linked polyethylene – XLPE). These cables consist of a phase conductor which is made of copper or aluminium, a metal screen and semiconductor layers over and under the insulation. Besides, above the screen, these usually have a swelling strip and aluminium lamination for longitudinal and transverse prevention of humidity penetration. Namely, the cross-linked polyethylene insulation is highly sensitive to the impact of humidity (the appearance of the so-called water twigs). Finally, there is the outer sheet of the single-core cable which is often made of HDPE (high-density polyethylene), [1].

The power cable consists of the three above mentioned single-core cables which are most usually laid in a trefoil formation and mutually touching thereat. Their transverse cross-section is graphically illustrated in Figure 1.



Slika 1 — Poprečni presjek kabelskog voda sastavljenog od jednožilnih kabela u trokutnom snopu
Figure 1 — Transverse intersection of the power cable consisting of one-core cables in a triangular truss

Oznake primijenjene na slici 1 imaju sljedeća značenja:

L1, L2 i L3 – faze dotičnog kabelskog voda,
r_p – srednji polumjer metalnog ekrana,
d_k – vanjski promjer jednožilnog kabela.

S obzirom da je ovdje riječ o kabelskim vodovima viših nazivnih napona (npr. 110 kV), oni pripadaju mreži koja radi s izravno uzemljenim zvjezdištima energetskih transformatora. Zbog toga spoj faznog vodiča sa zemljom u takvoj mreži predstavlja jednopolni kratki spoj. Mreža je ovdje galvanska veza spomenutih kabelskih vodova i pripadnih postrojenja istog nazivnog napona i frekvencije.

The symbols used in Figure 1 have the following meanings:

L1, L2 i L3 – phases of the concerned power cable,
r_p – mean radius of the metal screen,
d_k – outer diameter of the single-core cable.

Considering the fact that the matter at hand are power cables of higher nominal voltage (e.g. 110 kV), they belong to the network which operates with solidly earthed power transformer neutrals. Therefore, the circuit of the phase conductor and the ground in such a network represent a one-pole short circuit. The network is here a galvanic connection of the above power cables and the pertaining switchyards of the same nominal voltage and frequency.

Navedeni jednopolni kratki spoj (JKS) je praćen velikim strujama kvara. Riječ je o izrazito nesimetričnom kvaru, kod kojeg se razvijaju sustavi struja i napona direktnog, inverznog i nultog redoslijeda. Kod promatranog kabelskog voda, odgovarajuća nulta struja jednaka je sljedećem izrazu, [2]:

The said one-pole short circuit (OSC) is accompanied by large fault currents. The matter at hand is a greatly asymmetric fault at which current and voltage systems of direct, inverse and zero sequence develop. In the analysed power cable, the pertaining zero current is equal to the following expression, [2]:

$$\underline{I}_0 = \frac{1}{3} \cdot \left(\underline{I}_{\mathrm{L}1} + \underline{I}_{\mathrm{L}2} + \underline{I}_{\mathrm{L}3} \right), \tag{1}$$

gdje su $\underline{I}_{\mathrm{L}1}$, $\underline{I}_{\mathrm{L}2}$ i $\underline{I}_{\mathrm{L}3}$ struje dotičnog kvara u faznim vodičima L1, L2 i L3 kabelskog voda. One se dobivaju proračunom JKS-a u pripadnoj mreži. Za struje nultog redoslijeda je značajno da se zatvaraju pripadnim sustavom uzemljenja, kao i samom zemljom.

U konkretnom slučaju, pripadni sustav uzemljenja sastoji se od uzemljivača pojedinih postrojenja koji čine promatranu mrežu i metalnih ekrana nazočnih kabelskih vodova uzemljenih na oba kraja. Metalni ekrani, dakle, povezuju uzemljivače susjednih postrojenja. Ne dolazi pritom do odvođenja dijela struje JKS-a s metalnog ekrana u zemlju, jer je vanjski plašt (omotač) ovih kabela izrađen od HDPE. On ove kabele svrstava u skupinu tzv. u odnosu na zemlju izoliranih kabela.

Pri nastupu jednopolnoga kratkog spoja popratna raspodjela struja kvara u pripadnom sustavu uzemljenja, kao i u samoj zemlji, uspostavlja se u skladu s nazočnom elektromagnetskom spregom i potencijalima uzemljivača. U tom smislu, u situaciji pojedinačnih kabelskih vodova koji imaju vlastite kabelske trase, odgovarajuća raspodjela struje kvara u zemlji duž njihove trase, koja je posljedica elektromagnetske sprege, određuje se sljedećim izrazom, [3]:

where $\underline{I}_{\mathrm{L}1}$, $\underline{I}_{\mathrm{L}2}$ and $\underline{I}_{\mathrm{L}3}$ are currents of the concerned fault in phase conductors L1, L2 and L3 of the power cable. These are obtained by calculation of the OSC in the relevant network. Zero-sequence currents are characterized by the fact that they are closed by the pertaining earthing system as well as the ground itself.

In this particular case, the pertaining earthing system consists of the earthing grid of certain switchyards which make up the observed network and metal screens of the present power cables earthed at both ends. The metal screens therefore connect the earthing grids of neighbouring switchyards. Thereat, the abduction of part of the OSC current from the metal screen into the ground does not take place because the outer cable sheath (jacket) is made of HDPE. These cables are, hence, regarded as isolated in regards to the surrounding soil.

When the one-pole short circuit occurs, the accompanying distribution of fault currents in the pertaining earthing system, as well as in the ground itself, is established in accordance with the present electromagnetic coupling and the potentials of the grounding units. In that sense, in the situation of separate power cables which have own cable routes, adequate distribution of fault currents in the ground along their route which is the consequence of the electromagnetic coupling is determined according to the following expression, [3]:

$$\underline{I}_{\mathrm{z}} = \underline{r} \cdot 3\underline{I}_0 \tag{2}$$

pri čemu je $\underline{r}$ koeficijent redukcije dotičnog kabelskog voda. On se ovdje određuje pomoću sljedećeg izraza, [3], [4] i [5]:

whereat $\underline{r}$ is the reduction coefficient of the concerned power cable. It is determined here by virtue of the following expression, [3], [4] and [5]:

$$\underline{r} = \frac{\dfrac{R_{\mathrm{p}1}}{3}}{\dfrac{R_{\mathrm{p}1}}{3} + \dfrac{\omega\mu_0}{8} + \mathrm{j}\,\dfrac{\omega\mu_0}{2\pi} \cdot \ln\left(\dfrac{658}{\sqrt[3]{r_{\mathrm{p}} \cdot d_{\mathrm{k}}^2}} \cdot \sqrt{\dfrac{\rho}{f}} \right)} \tag{3}$$

u kojem novouvedene veličine znače:

R_{P1} – jedinični djelatni otpor metalnog ekrana, Ω/km,
ω – kružna frekvencija struje JKS-a, dana izrazom $\omega = 2\pi f$, gdje je $f = 50$ Hz,
μ_0 – permeabilnost slobodnog prostora, koja iznosi $4\pi \cdot 10^{-4}$ Vs/A·km,
ρ – prosječna električna otpornost (specifični električni otpor) tla duž trase promatranog kabelskog voda, Ωm.

Jedinični djelatni otpor ekrana, uvažavajući i njegovu temperaturnu ovisnost, može se odrediti sljedećim izrazom:

in which the newly-introduced elements mean:

R_{P1} – per-unit resistance of the metal screen, Ω/km,
ω – circular frequency of the OSC current presented by the expression $\omega = 2\pi f$, where $f = 50$ Hz, (3)
μ_0 – permeability of the vacuum which amounts to $4\pi \cdot 10^{-4}$ Vs/A·km,
ρ – mean specific soil electrical resistance along the route of the observed power cable, Ωm.

The per-unit resistance of the screen, taking into consideration also its temperature dependence, can be determined by virtue of the following expression:

$$R_{p1} = \rho_{cu} \cdot \frac{1\,000}{S_p} \cdot k_1 \cdot k_\upsilon \tag{4}$$

pri čemu su:

ρ_{cu} – električna otpornost (specifični električni otpor) bakra pri temperaturi 20 °C,
S_p – ukupna površina presjeka ekrana jednožilnog kabela, mm^2,
k_1 – koeficijent kojim se uzima u račun povećanje duljine žica ekrana radi uvijanja,
k_υ – koeficijet kojim se uzima u obzir utjecaj temperature na električni otpor ekrana, ovaj koeficijent određuje se prema IEC preporukama, [6].

U urbanim (gradskim) područjima radi se redovito o sustavima kabelskih vodova, koji dijelom ili u cijelosti imaju zajedničke kabelske trase. Tijekom spomenutog JKS-a dolazi stoga do međusobne elektromagnetske sprege među navedenim kabelskim vodovima, što utječe na popratnu raspodjelu struja kvara u njihovom sustavu uzemljenja, kao i u samoj zemlji. Zbog toga u ovom slučaju, dakako, nije moguće popratno strujno stanje u zemlji valjano opisati pojedinačnim (vlastitim) koeficijentima redukcije svakog od pripadnih kabelskih vodova, već samo odgovarajućom matricom koeficijenata redukcije promatranog sustava kabelskih vodova. Korištenje pojedinačnih (vlastitih) koeficijenata redukcije svakog od pripadnih kabelskih vodova, uz zanemarivanje međusobne elektromagnetske sprege među njima, u ovakvim slučajevima bi dovelo do velikih pogrešaka u izračunu raspodjele struja u zemlji.

Određivanje spomenute matrice koeficijenata redukcije stoga je upravo predmet ovoga rada. U njemu će se prezentirati, između ostalog, i teorijske podloge matematičkog modela proračuna

whereat it is as follows:

ρ_{cu} – specific electrical resistance of copper at the temperature of 20 °C,
S_p – total surface area of the single-core cable screen cross-section, mm^2,
k_1 – the coefficient by which increased length of the screen wires is taken into consideration because of the wrapping,
k_υ – the coefficient by which the impact of temperature on the screen electrical resistance is taken into consideration; this coefficient is determined following IEC recommendations, [6].

Urban (city) areas regularly have power cables systems with common cable routes partly or in full. During the said OSC, reciprocal electromagnetic coupling between the power cables occurs and this affects the pertaining distribution of fault currents in their earthing system and in the ground itself as well. Therefore, in this case, it is of course impossible to describe accurately the pertaining current situation in the ground by individual (self) reduction coefficients of each of the pertaining power cables but only by the adequate reduction coefficient matrix of the observed power cables system. Using individual (self) reduction coefficients of each of the pertaining power cables, along with ignoring the reciprocal electromagnetic coupling between them, in these cases, would bring about significant errors in the calculation of currents distribution in the ground.

Therefore, it is exactly the determination of the said reduction coefficient matrix that is the subject of this work. It will present, inter alia, theoretical matrice koeficijenata redukcije na primjeru općeg sustava kabelskih vodova. Valja naglasiti da je primjena matrice koeficijenata redukcije novina u odnosu na dosadašnje metode određivanja raspodjele struja jednopolnoga kratkog spoja u pasivnim dijelovima kabelskih sustava te popratnih struja u zemlji.

2 TEORIJSKE PODLOGE

Na slici 2 prikazan je primjer općeg sustava kabelskih vodova i njima incidentna postrojenja A, B, C i D s pripadnim energetskim transformatorima i nadomjesnim mrežama. Dotični sustav sastoji se, dakle, od $n = 5$ kabelskih vodova. Njihova numeracija prikazana je također na slici 2. Ona je odabrana sasvim proizvoljno. Navedeni kabelski vodovi sačinjeni su od jednožilnih kabela i položeni su u trokutnom snopu. Njihovi metalni ekrani uzemljeni su na oba kraja.

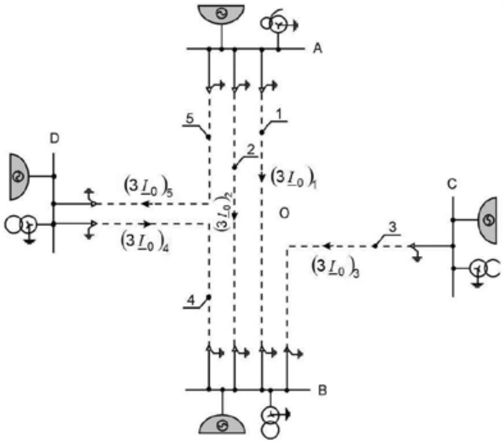
Osim toga, na slici 2 označeni su i smjerovi trostrukih nultih struja $(3\underline{I}_0)_i,\ i = 1, 2, \ldots, n,$ koje teku faznim vodičima navedenih kabelskih vodova. Ovi smjerovi dotičnih struja odgovaraju nastupu JKS-a u postrojenju B. Valja navesti da se vrijednosti dotičnih struja dobiju posebnim proračunom u pripadnoj mreži, kojoj je sustav prikazan na slici 2 tek jedan mali dio. Ove struje se stoga ovdje mogu smatrati poznatima.

bases of the mathematical model for the calculation of the reduction coefficient matrix on the example of the general power cables system. It should be pointed out that the application of the reduction coefficient matrix is new in relation to former methods for determination of the distribution of one-pole short circuit currents in the passive parts of the cable systems and the accompanying currents in the ground.

2 THEORETICAL BASES

Figure 2 shows the example of the general power cables system and their incidental switchyards A, B, C and D with pertaining power transformers and substitute networks. The concerned system consists therefore of $n = 5$ power cables. Their numeration is also shown in Figure 2. It has been chosen completely arbitrarily. The said power cables are made of single-core cables and laid in treefoil formation. Their metal screens are earthed at both ends.

Besides that, Figure 2 indicates also the directions of the triple zero currents $(3\underline{I}_0)_i,\ i = 1, 2, \ldots, n,$ which flow through phase conductors of the said power cables. These directions of the concerned currents coincide with the occurrence of the OSC in the B switchyard. It should be stated that the values of the concerned currents are obtained by special calculation in the pertaining network, of which the system shown in Figure 2 is only a small part. These currents can therefore be considered known here.



Slika 2 — Jednopolna shema općeg sustava kabelskih vodova i njima incidentnih postrojenja A, B, C i D s pripadnim energetskim transformatorima i nadomjesnim mrežama

Figure 2 — One-pole scheme of the general power cables system and their incidental switchyards A, B, C and D with pertaining power transformers and substitute networks

Budući da se navedeni kabelski vodovi sastoje od po tri jednožilna kabela složena u trokutnom snopu i da su njihovi metalni ekrani uzemljeni na

As the said power cables consist of three single-core cables arranged in treefoil formation and as their metal screens are earthed at both ends, each oba kraja, moguće je svaki kabelski vod zamijeniti s ekvivalentnim kabelom, kojem je metalni ekran određen sljedećim parametrima:

R_{eq1} – jedinični djelatni otpor metalnog ekrana ekvivalentnog kabela, Ω/km, u skladu s (3) njegova je vrijednost:

power cable can be replaced with the equivalent cable the metal screen of which is determined by the following parameters:

R_{eq1} – per-unit resistance of the equivalent cable metal screen, Ω/km, in accordance with (3), its value is:

$$R_{\mathrm{eq1}} = \frac{R_{\mathrm{p1}}}{3}\,, \tag{5}$$

r_{eq} – polumjer metalnog ekrana ekvivalentnog kabela, m, također prema (3), on iznosi:

r_{eq} – radius of the equivalent cable metal screen, m; also according to (3), it amounts to:

$$r_{\mathrm{eq}} = \sqrt[3]{r_{\mathrm{p}} \cdot d_{\mathrm{k}}^2}\;. \tag{6}$$

Temeljem relacija (5) i (6) uočava se da je ekvivalentiranje pojedinog kabelskog voda izvršeno u skladu s metodom srednjih geometrijskih udaljenosti. Ovaj korak smanjuje potreban broj jednadžbi sustava te pojednostavnjuje sam matematički model, uz istodobno osiguranje visoke točnosti rezultata proračuna. Naime, ekvivalentiranje kabelskog sustava prema (5) i (6) ne utječe na preciznost dobivenih rezultata proračuna. Ovo se može lako provjeriti.

U uvjetima nastupa JKS-a i danih struja $(3\underline{I}_0)_i$, $i = 1,\ 2,\ \ldots,\ n$, javit će se zbog elektromagnetske sprege i odgovarajuće struje u metalnim ekranima spomenutih kabelskih vodova, kao i struje u zemlji. Strujno stanje u metalnim ekranima spomenutih kabelskih vodova može se pritom odrediti metodom konturnih struja (metoda petlji). Može se postaviti sljedeća matrična jednadžba:

Based on the relations (5) and (6), it is evident that the replacement of the particular power cable was done in accordance with the mean geometrical distances method. This step reduces the necessary number of system equations and simplifies the mathematical model itself while ensuring high accuracy of the calculation results at the same time. Namely, the replacement of the cable system according to (5) and (6) does not affect the accuracy of the obtained calculation results. This can be verified easily.

In the conditions of occurrence of OSC and the given currents$(3\underline{I}_0)_i$, $i = 1,\ 2,\ \ldots,\ n$, because of the electromagnetic coupling, also adequate currents in the metal screens of the said power cables will appear as well as currents in the grounds. The current condition in the metal screens of the said power cables can then be determined by virtue of the contour currents method (the loop method). The following matrix equation can appear:

$$\underline{\boldsymbol{Z}}_{\mathrm{p}} \cdot \vec{\underline{I}}_{\mathrm{p}} = \vec{\underline{E}}_{\mathrm{p}} \tag{7}$$

u kojoj su:

$\underline{\boldsymbol{Z}}_{\mathrm{p}}$ – matrica vlastitih i međusobnih impedancija petlji, koju čine metalni ekrani spomenutih kabelskih vodova s utjecajem povratnog puta kroz tlo; riječ je o kvadratnoj matrici reda $(n,\ n)$,

$\vec{\underline{I}}_{\mathrm{p}}$ – vektor konturnih struja, koje teku metalnim ekranima spomenutih kabelskih vodova; općeniti oblik ovog vektora može se zapisati na sljedeći način:

in which it is as follows:

$\underline{\boldsymbol{Z}}_{\mathrm{p}}$ – the matrix of self and mutual loops impedances consisting of metal screens of the said power cables with the impact of the return path through the ground; the matter at hand is a $(n,\ n)$ square matrix.

$\vec{\underline{I}}_{\mathrm{p}}$ – the vector of contour currents which flow through the metal screens of the said power cables; the general form of this vector can be written as follows:

$$\vec{\underline{I}}_{\mathrm{p}} = \begin{bmatrix} {}^{1}\underline{I}_{\mathrm{p}} \\ \cdot \\ \cdot \\ \cdot \\ {}^{i}\underline{I}_{\mathrm{p}} \\ \cdot \\ \cdot \\ \cdot \\ {}^{n}\underline{I}_{\mathrm{p}} \end{bmatrix} \qquad (8)$$

$\vec{\underline{E}}_{\mathrm{p}}$ – vektor uzdužnih elektromotornih sila induciranih u metalnim ekranima spomenutih kabelskih vodova uslijed struja $\left(3\underline{I}_0\right)_i$, $i = 1,\ 2,\ \ldots,\ n$, koje teku faznim vodičima kabelskih vodova.

Matrica vlastitih i međusobnih impedancija petlji $\underline{\boldsymbol{Z}}_{\mathrm{p}}$ je simetrična u odnosu na svoju glavnu dijagonalu. Njeni dijagonalni i izvan dijagonalni članovi računaju se respektivno pomoću sljedećih izraza:

$\vec{\underline{E}}_{\mathrm{p}}$ – the vector of longitudinal electromotive forces induced in metal screens of the said power cables due to the currents $\left(3\underline{I}_0\right)_i$, $i = 1,\ 2,\ \ldots,\ n$, which flow through the phase conductors of the power cables.

The matrix of self and mutual loop impedances $\underline{\boldsymbol{Z}}_{\mathrm{p}}$ is symmetrical in relation to its main diagonal. Its diagonal and extra-diagonal members are calculated respectively by virtue of the following expressions:

$${}^{ii}\underline{Z}_{\mathrm{p}} = {}^{ii}\underline{Z}_{\mathrm{p1}} \cdot l_i, \qquad (9)$$

$${}^{ik}\underline{Z}_{\mathrm{p}} = {}^{ik}\underline{Z}_{\mathrm{p1}} \cdot l_{ik}, \qquad (10)$$

pri čemu su prema [3] i [7]:

whereat according to [3] and [7] it follows:

$${}^{ii}\underline{Z}_{\mathrm{p1}} = R_{\mathrm{eq1}} + \frac{\omega \cdot \mu_0}{8} + \mathrm{j}\frac{\omega \cdot \mu_0}{2\pi} \cdot \ln\left(\frac{658}{r_{\mathrm{eq}}} \cdot \sqrt{\frac{\rho}{f}}\right), \qquad (11)$$

$${}^{ik}\underline{Z}_{\mathrm{p1}} = \frac{\omega \cdot \mu_0}{8} + \mathrm{j}\frac{\omega \cdot \mu_0}{2\pi} \cdot \ln\left(\frac{658}{d_{ik}} \cdot \sqrt{\frac{\rho}{f}}\right), \qquad (12)$$

gdje je:

l_i – duljina i-tog, $i = 1, 2, \ldots, n$, kabelskog voda, km,

l_{ik} – duljina paralelnog vođenja između i-tog i k-tog, $k = 1, 2, \ldots, n$, kabelskog voda, km, ona, dakako, može biti jednaka nuli; primjerice, sa slike 2 se uočava da je $l_{35} = 0$, pri čemu je i odgovarajuća međusobna impedancija također jednaka nuli,

d_{ik} – srednja geometrijska udaljenost između i-tog i k-tog kabelskog voda,m.

Značenje ostalih veličina u izrazima (11) i (12) već prije je objašnjeno u Uvodu, te u izrazima (5) i (6). Valja navesti da su vlastite impedancije uvijek pozitivne, dok međusobne impedancije mogu biti pozitivne ili negativne. To ovisi o usvojenim smjerovima odgovarajućih konturnih struja. Ako su smjerovi odgovarajućih konturnih struja isti, tada

where it is as follows:

l_i – he length of the i^{th}, $i = 1, 2, \ldots, n$, power cable, km,

l_{ik} – the length of parallel guidance between the i^{th} and the k^{th}, $k = 1, 2, \ldots, n$, power cable, km; it can of course be equal to zero; for example, Figure 2 reveals that $l_{35} = 0$ whereat the pertaining reciprocal impedance is also equal to zero,

d_{ik} – mean geometrical distance between the i^{th} and the k^{th} power cable, m.

The meaning of the other elements in the expression (11) and (12) has already been explained in the Introduction and in the expressions (5) and (6). It should be stated that self impedances are always positive while mutual impedances can be either positive or negative. This depends on the adopted directions of the pertaining contour currents. If je pripadna međusobna impedancija pozitivna. U protivnom, ukoliko su smjerovi odgovarajućih konturnih struja suprotni, tada je pripadna međusobna impedancija negativna.

Vektor uzdužnih elektromotornih sila iz relacije (7), induciranih u metalnim ekranima kabelskih vodova, može se odrediti sljedećom matričnom jednadžbom:

the directions of the pertaining contour currents are the same, then the pertaining mutual impedance is positive. In the opposite case, if the directions of the pertaining contour currents are opposite, then the pertaining mutual impedance is negative.

The vector of longitudinal electromotive forces, induced in the power cables metal screens, from the relation (7), can be determined by virtue of the following matrix equation:

$$\vec{\underline{E}}_{\mathrm{p}} = \underline{\boldsymbol{Z}}_{\mathrm{m}} \cdot 3\vec{\underline{I}}_0 \ , \tag{13}$$

pri čemu su:

$\underline{\boldsymbol{Z}}_{\mathrm{m}}$ – matrica međusobnih impedancija petlji, koje čine metalni ekrani i fazni vodiči spomenutih kabelskih vodova s utjecajem povratnog puta kroz tlo; radi se također o kvadratnoj matrici reda (n, n),

$3\vec{\underline{I}}_0$ – vektor trostrukih nultih struja, koje teku faznim vodičima spomenutih kabelskih vodova; elementi ovog vektora su, dakle, struje prikazane na slici 2, a njegov oblik je općenito sljedeći:

whereat it is as follows:

$\underline{\boldsymbol{Z}}_{\mathrm{m}}$ – the matrix of mutual loops impedances consisting of metal screens and phase conductors of the said power cables with the impact of the return path through the ground; the matter at hand is also a (n, n) square matrix,

$3\vec{\underline{I}}_0$ – the vector of triple zero currents which flow through the phase conductors of the said power cables; thus, the elements of this vector are the currents shown in Figure 2 and its form is generally the following:

$$3\vec{\underline{I}}_0 = \begin{bmatrix} \left(3\vec{\underline{I}}_0\right)_1 \\ \vdots \\ \left(3\vec{\underline{I}}_0\right)_i \\ \vdots \\ \left(3\vec{\underline{I}}_0\right)_n \end{bmatrix} . \tag{14}$$

Matrica međusobnih impedancija petlji $\underline{\boldsymbol{Z}}_{\mathrm{m}}$ je također simetrična u odnosu na svoju glavnu dijagonalu. Njeni dijagonalni i izvandijagonalni elementi računaju se respektivno pomoću sljedećih izraza:

The matrix of mutual loop impedances $\underline{\boldsymbol{Z}}_{\mathrm{m}}$ is also symmetrical in relation to its main diagonal. Its diagonal and extra-diagonal elements are calculated respectively by virtue of the following expressions:

$${}^{ii}\underline{Z}_{\mathrm{m}} = {}^{ii}\underline{Z}_{\mathrm{m1}} \cdot l_i \ , \tag{15}$$

$${}^{ik}\underline{Z}_{\mathrm{m}} = {}^{ik}\underline{Z}_{\mathrm{m1}} \cdot l_{ik} \tag{16}$$

gdje su:

whereat it is as follows:

$${}^{ii}\underline{Z}_{\mathrm{m1}} = \frac{\omega \cdot \mu_0}{8} + \mathrm{j}\frac{\omega \cdot \mu_0}{2\pi} \cdot \ln\left(\frac{658}{r_{\mathrm{eq}}} \cdot \sqrt{\frac{\rho}{f}}\right) \tag{17}$$

$$ {}^{ik}\underline{Z}_{\mathrm{m}1} = \frac{\omega\cdot\mu_0}{8} + \mathrm{j}\frac{\omega\cdot\mu_0}{2\pi}\cdot\ln\left(\frac{658}{d_{ik}}\cdot\sqrt{\frac{\rho}{f}}\right) \qquad (18) $$

Na kraju valja spomenuti da je smjer konturnih struja koje teku metalnim ekranima kabelskih vodova, dan prema relaciji (8), usvojen takav da one teku u suprotnom smjeru od odgovarajućih struja $3\underline{I}_0$. Dakle, smjer struje ${}^1\underline{I}_\mathrm{p}$ je suprotan od smjera struje $(3\underline{I}_0)_1$, itd.

Uvrštenjem matrične jednadžbe (13) u matričnu jednadžbu (7) dobiva se:

Finally, it should be stated that the direction of contour currents which flow through the power cable metal screens, given according to the relation (8), is taken to be such as to allow them flowing contrary to the pertaining currents $3\underline{I}_0$. Therefore, the direction of the current ${}^1\underline{I}_\mathrm{p}$ is opposite to the direction of the current $(3\underline{I}_0)_1$, etc.

By introducing the matrix equation (13) into the matrix equation (7), the result is:

$$ \underline{\boldsymbol{Z}}_\mathrm{p}\cdot\vec{\underline{I}}_\mathrm{p} = \underline{\boldsymbol{Z}}_\mathrm{m}\cdot 3\vec{\underline{I}}_0 \qquad (19) $$

Iz dotične matrične jednadžbe slijedi:

From the concerned matrix equation it ensues:

$$ \vec{\underline{I}}_\mathrm{p} = \underline{\boldsymbol{Z}}_\mathrm{p}^{-1}\cdot\underline{\boldsymbol{Z}}_\mathrm{m}\cdot 3\vec{\underline{I}}_0 \qquad (20) $$

Nadalje, odgovarajuće struje u zemlji mogu se odrediti sljedećom matričnom jednadžbom:

Furthermore, the pertaining currents in the ground can be determined by the following matrix equation:

$$ \vec{\underline{I}}_\mathrm{z} = 3\vec{\underline{I}}_0 - \vec{\underline{I}}_\mathrm{p} \qquad (21) $$

gdje je $\vec{\underline{I}}_\mathrm{z}$ vektor odgovarajućih struja u zemlji, koji ima sljedeći opći oblik:

where $\vec{\underline{I}}_\mathrm{z}$ is the vector of pertaining currents in the earth and it has the following form:

$$ \vec{\underline{I}}_\mathrm{z} = \begin{bmatrix} {}^1\vec{\underline{I}}_\mathrm{z} \\ \cdot \\ \cdot \\ \cdot \\ {}^i\vec{\underline{I}}_\mathrm{z} \\ \cdot \\ \cdot \\ \cdot \\ {}^n\vec{\underline{I}}_\mathrm{z} \end{bmatrix} . \qquad (22) $$

Daljnjim uvrštenjem matrične jednadžbe (20) u (21) dobiva se:

Further introduction of the matrix equation (20) into (21) results in:

$$ \vec{\underline{I}}_\mathrm{p} = \left(\boldsymbol{E} - \underline{\boldsymbol{Z}}_\mathrm{p}\cdot\underline{\boldsymbol{Z}}_\mathrm{m}\right)3\vec{\underline{I}}_0 \qquad (23) $$

pri čemu je $\boldsymbol{E}$ – jedinična matrica reda (n, n). Ova matrica u svojoj glavnoj dijagonali ima jedinice.

whereat $\boldsymbol{E}$ is the (n, n) unit matrix. This matrix has units in its main diagonal. All of its extra-diagonal

Svi njeni izvandijagonalni elementi jednaki su nuli.

elements equal zero.

Uvede li se sljedeća supstitucija:

If the following substitution is introduced:

$$\underline{\boldsymbol{r}} = \boldsymbol{E} - \underline{\boldsymbol{Z}}_{\mathrm{p}}^{-1} \cdot \underline{\boldsymbol{Z}}_{\mathrm{m}} \ , \tag{24}$$

može se matrična jednadžba (23) napisati u sljedećem obliku:

the matrix equation (23) can be written in the following form:

$$\vec{\underline{I}}_{\mathrm{z}} = \underline{\boldsymbol{r}} \cdot 3\vec{\underline{I}}_{0} \ . \tag{25}$$

Pritom je $\underline{\boldsymbol{r}}$ – matrica koeficijenata redukcije promatranog sustava kabelskih vodova. Riječ je ponovno o kvadratnoj matrici reda (n, n). Za dotičnu matricu je značajno da njeni elementi ovise o elektromagnetskim i geometrijskim značajkama metalnih ekrana kabelskih vodova, zatim o njihovom smještaju (konfiguraciji), kao i o geofizikalnim svojstvima (električnoj otpornosti tla) njihove trase. Oni također ovise i o frekvenciji struja koje teku spomenutim kabelskim vodovima. U uvjetima nastupa JKS-a riječ je, dakako, o frekvenciji $f = 50$ Hz.

Na temelju prezentirane teorije izrađen je odgovarajući računalni program. Isti je napisan u programskom jeziku Fortran 95, [8]. Pomoću razvijenog računalnog programa može se, dakle, odrediti odgovarajuća matrica koeficijenata redukcije po volji složenog sustava kabelskih vodova, kao i popratna raspodjela struja u zemlji za zadana strujna opterećenja faznih vodiča navedenih kabelskih vodova.

Na kraju, zanimljivo je navesti da je matrična jednadžba dana izrazom (25) oblikom slična izrazu (2), koji se odnosi na slučaj samo jednog kabelskog voda. Analogno tomu, matrična jednadžba dana izrazom (24) u slučaju samo jednog kabelskog voda poprima sljedeći oblik:

Thereat, $\underline{\boldsymbol{r}}$ is the reduction coefficient matrix of the observed power cables system. The matter at hand is again a (n, n) square matrix. The concerned matrix is characterized by its elements being dependant on electromagnetic and geometrical properties of power cable metal screens, on their positioning (configuration), as well as on the geophysical properties (specific ground electrical resistance) of their route. These also depend on the frequency of currents which flow through the said power cables. In the conditions of occurrence of OSC, the concerned frequency is of course $f = 50$ Hz.

Based on the presented theory, adequate computer software has been developed. It is written in the Fortran 95 programming language, [8]. By virtue of the developed computer programme, the adequate reduction coefficient matrix can of course be determined as required by the complex power cables system, as well as the pertaining distribution of currents in the ground for the given current loads of the said power cables' phase conductors.

Finally, it is interesting to state that the matrix equation given by the expression (25) has a form similar to expression (2) which relates to the case of only one power cable. Analogously, the matrix equation given by the expression (24) in case of only one power cable assumes the following form:

$$\underline{r} = 1 - \frac{\underline{Z}_{\mathrm{m}}}{\underline{Z}_{\mathrm{p}}} \ . \tag{26}$$

U skladu s izrazima (9), (11), (15) i (17) ovdje je:

In accordance with the expressions (9), (11), (15) and (17), here it is as follows:

$$\frac{\underline{Z}_{\mathrm{m}}}{\underline{Z}_{\mathrm{p}}} = \frac{\dfrac{\omega \cdot \mu_0}{8} + \mathrm{j}\dfrac{\omega \cdot \mu_0}{2\pi} \cdot \ln\left(\dfrac{658}{r_{\mathrm{eq}}} \cdot \sqrt{\dfrac{\rho}{f}}\right)}{R_{\mathrm{eq1}} + \dfrac{\omega \cdot \mu_0}{8} + \mathrm{j}\dfrac{\omega \cdot \mu_0}{2\pi} \cdot \ln\left(\dfrac{658}{r_{\mathrm{eq}}} \cdot \sqrt{\dfrac{\rho}{f}}\right)} \ . \tag{27}$$

Uvrštenjem izraza (27) u (26) slijedi:

The introduction of the expression (27) into (26) results in:

$$\underline{r} = \frac{R_{\text{eq}1}}{R_{\text{eq}1} + \frac{\omega \cdot \mu_0}{8} + \text{j}\frac{\omega \cdot \mu_0}{2\pi} \cdot \ln\left(\frac{658}{r_{\text{eq}}} \cdot \sqrt{\frac{\rho}{f}}\right)} \quad . \tag{28}$$

Dakle, uz (5) i (6) izraz (28) je istovjetan izrazu (3), koji je prije naveden kao koeficijent redukcije samo jednog kabelskog voda.

3 PRIMJER PRORAČUNA

Kao primjer proračuna odabran je sustav kabelskih vodova prikazan na slici 2. Neka se radi o kabelskim vodovima nazivnog napona 110 kV, koji se sastoje od jednožilnih kabela s faznim vodičem od aluminija presjeka 1 000 mm². Njihova izolacija je od umreženog polietilena, a metalni ekran od helikoidno motanih okruglih bakrenih žica ukupnog presjeka 95 mm². Jedinični djelatni otpor i srednji polumjer metalnog ekrana respektivno iznose $R_{\text{P1}} = 0{,}226\ \Omega/\text{km}$ i $r_{\text{P1}} = 37\ \text{mm}$, [9]. Vanjski plašt jednožilnog kabela je od HDPE, a njegov vanjski promjer iznosi $d_{\text{k}} = 84\ \text{mm}$.

Temeljem navedenih podataka, te izraza (5) i (6), slijedi da je fiktivni ekvivalentni kabel, svakog od kabelskih sustava, dan sljedećim veličinama $R_{\text{eq 1}} = 0{,}075\ \Omega/\text{km}$ i $r_{\text{eq}} = 0{,}0964\ \text{m}$.

Konfiguracija i numeracija navedenih kabelskih vodova prikazani su također na slici 2. Neka se radi o sljedećim njihovim duljinama: $l_1 = l_2 = 3{,}5\ \text{km}$, $l_3 = 6\ \text{km}$, $l_4 = 4{,}5\ \text{km}$ i $l_5 = 5\ \text{km}$.

Prema slici 2, kabelski vodovi 1, 2 i 5 na potezu A – O imaju zajedničku kabelsku trasu duljine 2 km. To isto imaju i kabelski vodovi 1, 2, 3 i 4 na potezu B – O u duljini 1,5 km, te kabelski vodovi 4 i 5 na potezu D – O u duljini 3 km. Nadalje, međusobni razmak između susjednih kabelskih vodova smještenih u zajedničke kabelske trase iznosi 0,6 m.

Konačno, prosječna električna otpornost (prosječni specifični električni otpor) tla duž trasa navedenih kabelskih vodova neka je svugdje isti i iznosi $\rho = 200\ \Omega\text{m}$.

Korištenjem spomenutog računalnog programa dobivena je matrica koeficijenata redukcije promatranog sustava kabelskih vodova. Uz navedene podatke, ova matrica je izračunata za $f = 50$ Hz i $\mu_0 = 4\pi \cdot 10^{-4}\ \text{Vs/A}\cdot\text{km}$. Ona je prikazana izrazom (29):

Therefore, with (5) and (6), the expression (28) is equal to the expression (3) which has been stated above as the reduction coefficient of only one power cable.

3 CALCULATION EXAMPLE

As an example of calculation, the power cables system shown in Figure 2 was chosen. Let us say that these are power cables of nominal voltage of 110 kV and consisting of single-core cables with an aluminium phase conductor with the cross-section area of 1 000 mm². Their insulation is made of cross-linked polyethylene and a metal screen of helicoidally wrapped circular copper wires of total cross-section area of 95 mm². Per-unit resistance and mean metal screen radius respectively amount to $R_{\text{P1}} = 0{,}226\ \Omega/\text{km}$ and $r_{\text{P1}} = 37\ \text{mm}$, [9]. The outer single-core able sheath is made of HDPE and its outer diameter amounts to $d_{\text{k}} = 84\ \text{mm}$.

Based on the stated data and based on the expressions (5) and (6), it ensues that the fictive equivalent cable, of each of the cable systems, is given by the following dimensions $R_{\text{eq 1}} = 0{,}075\ \Omega/\text{km}$ and $r_{\text{eq}} = 0{,}0964\ \text{m}$.

The configuration and the numeration of the said power cables are also shown in Figure 2. Let us say that their lengths are as follows: $l_1 = l_2 = 3{,}5\ \text{km}$, $l_3 = 6\ \text{km}$, $l_4 = 4{,}5\ \text{km}$ and $l_5 = 5\ \text{km}$.

According to Figure 2, the power cables 1, 2 and 5 on the A – O stretch have a common 2 km long cable route. The same pertains to the power cables 1, 2, 3, and 4 on the B – O stretch in the length of 1,5 km and power cables 4 and 5 on the D – O stretch in the length of 3 km. Furthermore, the interspacing between the neighbouring power cables positioned in common cable routes amounts to 0,6 m.

Finally, let us say that the mean specific ground electrical resistance along the routes of the said power cables is the same everywhere and amounts to $\rho = 200\ \Omega\text{m}$.

Use of the said computer programme enabled the reduction coefficient matrix of the observed power cables system. With the mentioned data, this matrix was calculated for $f = 50$ Hz and $\mu_0 = 4\pi \cdot 10^{-4}$ Vs/A·km. It is shown by the expression (29):

$$\underline{r} = \begin{bmatrix} 0{,}123 - j0{,}261 & -0{,}094 + j0{,}148 & -0{,}014 + j0{,}033 & -0{,}015 + j0{,}049 & -0{,}018 + j0{,}054 \\ -0{,}094 + j0{,}148 & 0{,}149 - j0{,}277 & -0{,}001 + j0{,}017 & -0{,}058 + j0{,}080 & -0{,}058 + j0{,}083 \\ -0{,}010 + j0{,}024 & -0{,}001 + j0{,}012 & 0{,}030 - j0{,}134 & -0{,}004 + j0{,}017 & 0{,}003 - j0{,}006 \\ -0{,}013 + j0{,}043 & -0{,}050 + j0{,}070 & -0{,}004 + j0{,}020 & 0{,}089 - j0{,}211 & 0{,}074 - j0{,}126 \\ -0{,}015 + j0{,}047 & -0{,}051 + j0{,}073 & 0{,}003 - j0{,}007 & 0{,}074 - j0{,}126 & 0{,}087 - j0{,}209 \end{bmatrix} . \quad (29)$$

Primjera radi, korištenjem izraza (3), odnosno (27), odgovarajući koeficijent redukcije jednog od navedenih kabelskih vodova iznosi:

$$\underline{r} = 0{,}118\angle -78{,}7^\circ \,. \quad (30)$$

U tablici 1 (stupci 3 i 4) prikazane su raspodjele trostrukih nultih struja kroz fazne vodiče navedenih kabelskih vodova, pri neistodobnim nastupima JKS-a u postrojenjima A, B, C i D. Osim toga, u istoj tablici (stupci 5 i 6) prikazane su i odgovarajuće trostruke nulte struje kroz fazne vodiče navedenih kabelskih vodova za usvojeno njihovo usmjerenje prema slici 2, također pri neistodobnim nastupima JKS-a u spomenutim postrojenjima. Naime, matrica koeficijenata redukcije promatranog sustava kabelskih vodova određena je za usvojeno usmjerenje trostrukih nultih struja prema slici 2.

To exemplify, the use of the expression (3), that is, (27), the pertaining reduction coefficient of one of the said power cables amounts to:

Table 1 (columns 3 and 4) shows the distributions of the triple zero currents through the phase conductors of the said power cables at non-simultaneous occurrences of the OSC in the switchyards A, B, C and D. Besides that, the same table (columns 5 and 6) also shows the pertaining triple zero currents through the phase conductors of the said power cables for their direction adopted according to Figure 2, also at non-simultaneous occurrences of the OSC in the said switchyards. Namely, the reduction coefficient matrix of the observed power cables system is determined for the adopted direction of triple zero currents according to Figure 2.

Tablica 1 – Raspodjela trostrukih nultih struja kroz fazne vodiče navedenih kabelskih vodova (KB), pri neistodobnim nastupima JKS-a u postrojenjima A, B, C i D

Table 1 – Distribution of triple zero currents through the phase conductors of the said power cables (KB) at non-simultaneous occurrences of the OSC in the switchyards A, B, C and D

Mjesto JKS-a / OSC location	Oznaka KB-a / KB symbol	Raspodjela struja kvara / Fault currents distribution			
		Od – do / From - to	$3\underline{I}_0$, kA ∠°	Od – do / From - to	$3\underline{I}_0$, kA ∠°
A	1	B – A	$2{,}5\angle -85^\circ$	A – B	$2{,}5\angle 95^\circ$
	2	B – A	$2{,}5\angle -85^\circ$	A – B	$2{,}5\angle 95^\circ$
	3	C – B	$2{,}0\angle -75^\circ$	C – B	$2{,}0\angle -75^\circ$
	4	B – D	$1{,}1\angle -80^\circ$	D – B	$1{,}1\angle 100^\circ$
	5	D – A	$1{,}9\angle -66^\circ$	A – D	$1{,}9\angle 114^\circ$
B	1	A – B	$8{,}6\angle -77^\circ$	A – B	$8{,}6\angle -77^\circ$
	2	A – B	$8{,}6\angle -77^\circ$	A – B	$8{,}6\angle -77^\circ$
	3	C – B	$2{,}7\angle -87^\circ$	C – B	$2{,}7\angle -87^\circ$
	4	D – B	$3{,}4\angle -109^\circ$	D – B	$3{,}4\angle -109^\circ$
	5	A – D	$1{,}4\angle -160^\circ$	A – D	$1{,}4\angle -160^\circ$
C	1	A – B	$4{,}0\angle -75^\circ$	A – B	$4{,}0\angle -75^\circ$
	2	A – B	$4{,}0\angle -75^\circ$	A – B	$4{,}0\angle -75^\circ$
	3	B – C	$10{,}1\angle -82^\circ$	C – B	$10{,}1\angle 98^\circ$
	4	D – B	$1{,}0\angle -107^\circ$	D – B	$1{,}0\angle -107^\circ$
	5	A – D	$0{,}9\angle -177^\circ$	A – D	$0{,}9\angle 177^\circ$
D	1	A – B	$3{,}2\angle -114^\circ$	A – B	$3{,}2\angle -114^\circ$
	2	A – B	$3{,}2\angle -114^\circ$	A – B	$3{,}2\angle -114^\circ$
	3	C – B	$1{,}9\angle -80^\circ$	C – B	$1{,}9\angle -80^\circ$
	4	B – D	$9{,}0\angle -104^\circ$	D – B	$9{,}0\angle 76^\circ$
	5	A - D	$10{,}9\angle -56^\circ$	A – D	$10{,}9\angle -56^\circ$

Daljnjom primjenom spomenutog računalnog programa, korištenjem raspodjela trostrukih nultih struja danih u tablici 1 (stupac 6), dobivene su odgovarajuće raspodjele struja u zemlji duž navedenih kabelskih vodova, u slučajevima neistodobnih nastupa JKS-a u postrojenjima A, B, C i D. Rezultati dotičnih proračuna predočeni su u tablici 2.

Further application of the said computer programme and the use of the distributions of the triple zero currents given in Table 1 (column 6) result in the pertaining distributions of the currents in the ground along the said power cables, in cases of non-simultaneous occurrence of the OSC in the switchyards A, B, C and D. The results of the concerned calculations are presented in Table 2.

Tablica 2 – Raspodjela popratnih struja u zemlji duž navedenih kabelskih vodova (KB), pri neistodobnim nastupima JKS-a u postrojenjima A, B, C i D
Table 2 – Distribution of accompanying currents through the said power cables (KB) at non-simultaneous occurrences of the OSC in the switchyards A, B, C and D

Oznaka KB-a / KB symbol	Od – do / From - to	Struje $\underline{I_z,\ \mathrm{A}\angle^\circ}$ pri nastupima JKS-a u / currents at occurrence of the OSC in:			
		A	B	C	D
1	A – B	$204\angle 11{,}8^\circ$	$757\angle 220^\circ$	$795\angle 215{,}4^\circ$	$682\angle 125^\circ$
2	A – B	$178\angle -21{,}8^\circ$	$850\angle 235^\circ$	$630\angle 222{,}3^\circ$	$1\,106\angle 140^\circ$
3	C – B	$376\angle 205^\circ$	$63\angle 109{,}5^\circ$	$1\,549\angle 21{,}6^\circ$	$352\angle 209^\circ$
4	D – B	$243\angle 54{,}6^\circ$	$843\angle 93{,}9^\circ$	$401\angle 105{,}7^\circ$	$2\,089\angle -31^\circ$
5	A – D	$249\angle 61{,}5^\circ$	$922\angle 80{,}1^\circ$	$629\angle 66{,}8^\circ$	$1\,704\angle -79^\circ$

Valja navesti da se struje u tablici 2 mogu dalje iskoristiti, primjerice, za određivanje opasnih napona koji se mogu inducirati u telekomunikacijskim (TK) vodovima sa žičanim vodičima i metalnim masama (kovinski cjevovodi i sl.), smještenim u području elektromagnetskog utjecaja promatranog sustava kabelskih vodova.

4 ZAKLJUČAK

U sustavu kabelskih vodova, u uvjetima nastupa jednopolnoga kratkog spoja, dolazi do međusobne elektromagnetske sprege među pripadnim kabelskim vodovima. To utječe na raspodjelu popratne struje kvara u pripadnom sustavu uzemljenja, kao i u samoj zemlji.

Dotična raspodjela struja kvara ne može se egzaktno odrediti korištenjem pojedinačnih koeficijenata redukcije svakog od pripadnih kabelskih vodova, već samo uporabom odgovarajuće matrice koeficijenata redukcije promatranog sustava kabelskih vodova.

Teorijske podloge određivanja dotične matrice koeficijenata redukcije izvorno su prikazane u ovom radu. Za matricu koeficijenata redukcije je značajno da njeni elementi ovise o:

- elektromagnetskim i geometrijskim značajkama metalnih ekrana pripadnih kabelskih vodova, zatim o
- njihovom smještaju (konfiguraciji), te o

It should be mentioned that the currents in Table 2 can be used further, for example, for the determination of dangerous voltages which can be induced in telecommunication (TC) cables with wire conductors and metal masses (metal pipelines, etc.), located in the area of electromagnetic impact of the observed power cables system.

4 CONCLUSION

In the power cables system, in the conditions of occurrence of one-pole short circuit, there occurs mutual electromagnetic coupling between the pertaining power cables. That affects the distribution of the accompanying fault current in the pertaining earthing system, as well as in the ground itself.

The concerned distribution of the fault currents cannot be determined exactly by using individual reduction coefficients of each of the pertaining power cables but only by using the adequate reduction coefficient matrix of the observed power cables system.

Theoretical bases for the determination of the concerned reduction coefficient matrix are shown originally in this work. The reduction coefficient matrix is characterized by having elements dependant on:

- electromagnetic and geometric properties of the metal screens of the pertaining power ca-

- geofizikalnim svojstvima njihove trase, kao i o
- frekvenciji struja koje teku dotičnim kabelskim vodovima.

U radu je također prikazana i primjena iznesene teorije na primjeru općeg sustava kabelskih vodova nazivnog napona 110 kV. Izračunate struje u zemlji mogu se dalje iskoristiti npr. za određivanje opasnih induciranih napona u telekomunikacijskim vodovima sa žičanim vodičima i drugim metalnim masama, smještenim u području elektromagnetskog utjecaja sustava kabelskih vodova.

Na kraju valja naglasiti da se do iste raspodjele struja u pripadnom sustavu uzemljenja, kao i u samoj zemlji može doći i drugim metodama i postupcima. Primjerice, primjenom tehnike konačnih elemenata na razmatrani sustav, i sl. Prednost ovog pristupa, korištenjem matrice koeficijenata redukcije sustava kabelskih vodova, iskazuje se u njegovoj jednostavnosti, uz istodobnu iznimno visoku točnost.

bles, and then on

- their positioning (configuration), and on
- the geophysical properties of their route, as well as on
- the frequency of the currents flowing through the concerned power cables.

The work also depicts the application of the presented theory on the example of the general system of power cables with nominal voltage of 110 kV. The calculated currents in the earth can further serve, e.g. for the determination of dangerous induced voltages in telecommunication cables with wire conductors and other metal masses, located in the area of electromagnetic impact of the power cables system.

Finally, it needs to be pointed out that the same distribution of currents in the pertaining earthing system, as well as in the ground itself, can also be obtained by other methods and procedures. For example, by applying the finite element technique on the observed system, etc. The advantage of this approach of using the reduction coefficient matrix of the power cables system is in its simplicity and extremely high accuracy.

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Uredništvo primilo rukopis:
2009-05-20

Prihvaćeno:
2009-06-08

Manuscript received on:
2009-05-20

Accepted on:
2009-06-08