NAPON NUL-VODIČA MREŽE NISKOG NAPONA ZA VRIJEME ZEMLJOSPOJA U MREŽI SREDNJEG NAPONA

THE NEUTRAL CONDUCTOR VOLTAGE IN A MEDIUM-VOLTAGE NETWORK DURING A GROUND FAULT

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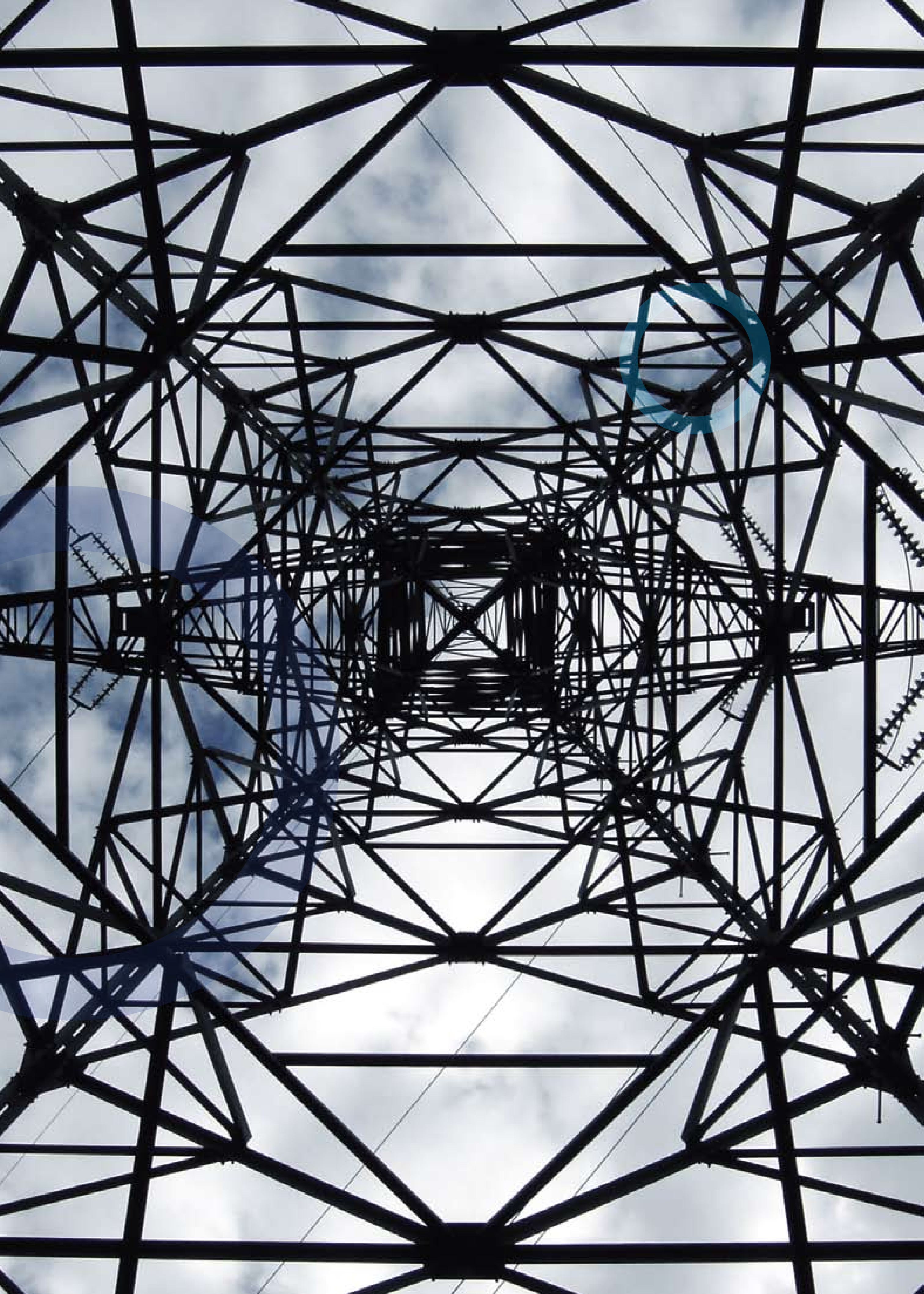
Od svih zemljospojeva koji se mogu pojaviti u mrežama srednjeg napona sa stanovišta sigurnosti ljudi i opreme najproblematičniji je zemljospoj u trafostanici srednji napon/niski napon. Naime, uzemljivački sustav mreže niskog napona direktno je povezan s uzemljivačem trafostanice. Stoga se svako povećanje potencijala uzemljivača trafostanice direktno prenosi preko nul-vodiča u instalaciju potrošača. Iz navedenih razloga u ovom radu detaljnije se obrađuje problematika određivanja napona nul-vodiča u mreži niskog napona za vrijeme zemljospoja na razini srednjeg napona u pojnoj trafostanici koja je element mreže srednjeg napona s izoliranim zvjezdištem. Prezentiran je računski model za analizu napona nul-vodiča u realnim distribucijskim mrežama. Analizirane su dvije karakteristične distribucijske mreže položene na kraškom terenu. Dobiveni rezultati su uspoređeni s rezultatima mjerenja.

Of all the ground faults that can occur in medium-voltage networks from the standpoint of human and equipment safety, the most problematic is a ground fault in a medium-voltage/low-voltage substation. The grounding system of a low-voltage network is directly connected to the grounding electrode of the substation. Therefore, each increase in the potential of the grounding electrode of the substation is transmitted directly via the neutral conductor into the customer's installation. For these reasons, in this article a detailed investigation is presented of the problem of determining the neutral conductor voltage in a low-voltage network during a ground fault at the medium-voltage level in a supply substation that is an element of a medium-voltage network with an isolated neutral point (star point). A computer model is presented for the analysis of the neutral conductor voltage in actual distribution networks. Two characteristic distribution networks located on karstic terrain are analyzed. The results obtained are compared to the results of measurements.

Ključne riječi: distribucijska mreža, napon nul-vodiča, niski napon, potencijal, srednji napon, zemljospoj
Key words: distribution network, ground fault, low-voltage, medium-voltage, neutral conductor voltage, potential

Majstrović, M., Napon nul-vodiča mreže niskog napona ..., Energija god. 57(2008), br. 3., str. 328-349
Majstrović, M., The Neutral Conductor Voltage in a Medium-Voltage Network ..., Energija, Vol. 57(2008), No.3, pp. 328-349

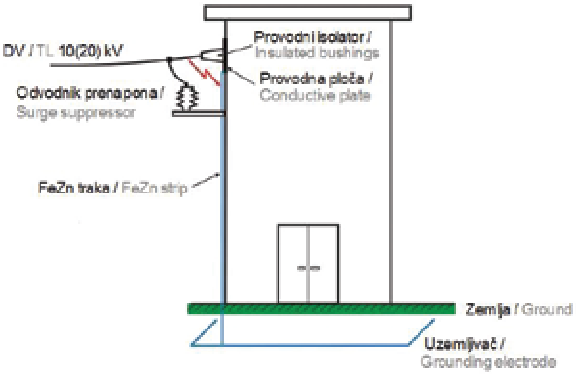


1 UVOD

Distribucijske trafostanice srednji napon/niski napon ((TS SN/NN) široko su rasprostranjeni objekti. Prema zadnjim dostupnim tehničkim podacima na području HEP Operator distibucijskog sustava (HEP ODS), Distribucijsko područje (DP) Elektrodalmacija Split u pogonu je 2 541 TS 10(20)/0,4 kV, od kojih je 2 232 u vlasništvu Hrvatske elektroprivrede (HEP d.d.), a ostale su u vlasništvu drugih pravnih subjekata. Za ilustraciju slika 1 prikazuje TS 10(20)/0,4 kV tipa tornjić na koju je preko provodnih izolatora priključen 10(20) kV zračni vod. Provodna ploča na koju se učvršćuje provodni izolator najčešće je metalna i uzemljena. Probojem provodnog izolatora u jednoj fazi događa se zemljospoj.

1 INTRODUCTION

Medium-voltage/low-voltage distribution substations are widespread. According to the most recent available technical data, within the territory of the HEP Distribution System Operator (HEP ODS), Distribution Region (DP) Elektrodalmacija Split, there are 2 541 10(20)/0,4 kV substations in operation, of which 2 232 are owned by HEP d.d. (Hrvatska elektroprivreda – The Croatian Power Company) and the remaining are under the ownership of other legal subjects. As an illustration, Figure 1 shows a 10(20)/0,4 kV substation to which a 10(20) kV aerial line is connected using insulated bushings. The conductive plate to which the insulated bushings are fastened is most often metal and grounded. A ground fault can occur due to the breakdown of an insulated bushing in a single phase.



Slika 1 — TS 10(20)/0,4 kV tipa tornjić
Figure 1 — 10(20)/0,4 kV substation

Slično vrijedi i za ostale tipove trafostanica koji se pojavljuju u distribucijskoj praksi. U slučaju spomenutog zemljospoja uzemljivač pogođene trafostanice dolazi na puni potencijal kvara i taj se potencijal preko nul-vodiča, koji je vezan za uzemljivački sustav ove trafostanice prenosi do instalacija niskog napona potrošača. Potencijal nul-vodiča u instalaciji potrošača ovisi o više faktora, ovisno o tome napaja li se potrošač podzemnim kabelom niskog napona uz položeno uzemljivačko uže ili traku ili se napaja zračnim vodom (samonosivim kabelskim snopom SKS ili golim vodičima). Pri tom kod napajanja zračnim vodom potencijal nulvodiča najviše ovisi o tome na koliko je stupnih mjesta nul-vodič uzemljen duž izvoda i koliko su kvalitetno izvedeni uzemljivači tih stupova.

U ovom radu analiziraju se razni slučajevi prenošenja potencijala u mrežu niskog napona pri zemljospoju u neuzemljenoj mreži srednjeg napona na kraškom terenu, gdje specifični otpor zemlje znatno ovisi o vremenskim prilikama

The same also applies to the other types of substations in distribution practice. In the event of a ground fault, the grounding electrode of the affected substation reaches fault potential. This potential is transferred via the neutral conductor, which is connected to the grounding system of the substation, to the customer's low-voltage installation. The neutral conductor potential in the customer's installation depends on several factors, according to whether the customer is supplied via a low-voltage underground cable together with a grounding cable or a grounding strip or is supplied via an aerial line (aerial bundled conductors or bare conductors). When supplied via an aerial line, the neutral conductor voltage primarily depends upon the number of pole sites at which the neutral conductor is grounded along the feeder and the quality of the installation of the grounding electrodes of the poles.

In this article, various cases of the transfer of potential in a low-voltage network during ground faults in an ungrounded medium-voltage network on karstic terrain are analyzed, where the specific soil resis-

(padalinama). Za primjer odabrane su dvije distribucijske mreže DP-a Elektrodalmacija Split kod kojih su mreže 10(20) kV u pogonu s izoliranim zvjezdištem. Analiza je provedena za dva karakteristična vremenska razdoblja (vlažni i suhi). Rezultati dobiveni računskim putem uspoređeni su s rezultatima dobivenim mjerenjem na terenu.

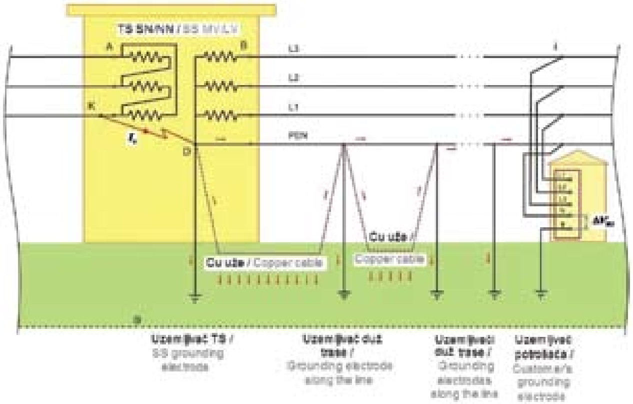
2 PRORAČUN STRUJE ZEMLJOSPOJA

Napajanje TS SN/NN izvodi se kabelskim i/ili zračnim vodovima srednjeg napona. Kabelski vodovi izvode se najčešće kabelima čiji su metalni plaštevi uzemljeni u pripadnim trafostanicama. Paralelno sa svakim kabelom polaže se uzemljivačko uže ili traka. U ovom radu, radi preglednosti postupka, najprije će se analizirati zemljospoj u neuzemljenoj mreži srednjeg napona sa zračnim vodovima bez dozemnog užeta, a potom u mreži s kabelskim vodovima. Izvodi niskog napona iz TS SN/NN izvode se u praksi kao zračni (goli vodiči i/ili SKS) i/ili kabelski. Kod zračne mreže niskog napona uzemljivači se izvode kod pojedinih stupova duž trase voda gdje se uzemljuje nul-vodič. U slučaju kabelske mreže uz kabele niskog napona polaže se uzemljivačko uže ili traka (na slici 2 prikazano crtkanom linijom – Cu uže).

tivity significantly depends upon the weather conditions (precipitation). As an example, two distribution networks have been chosen within DP Elektrodalmacija Split, where 10(20) kV networks are in operation with isolated neutral points. Analysis was performed for two characteristic seasons of the year (rainy and dry). The results obtained by computer are compared to the results obtained from measurements on the terrain.

2 CALCULATION OF GROUND FAULT CURRENT

A medium-voltage/low-voltage substation is supplied via medium-voltage cable lines and/or aerial lines. Cable lines most often use cables whose metal sheaths are grounded in the corresponding substations. Parallel to each cable is a grounding cable or strip. In this article, for purposes of clarity, an analysis will first be presented of a ground fault in an ungrounded medium-voltage network with aerial lines but without a grounding cable, and then in a network with cable lines. A low-voltage feeder from a medium-voltage/low-voltage substation is in practice an aerial (bare conductors and/or bundled cables and/or cables). In a low-voltage aerial network, the grounding electrodes are installed at some poles along the line where the neutral conductor is grounded. In the case of a cable network, along the low-voltage cable is a grounding cable or grounding strip (shown in Figure 2 by the dotted line – copper cable).



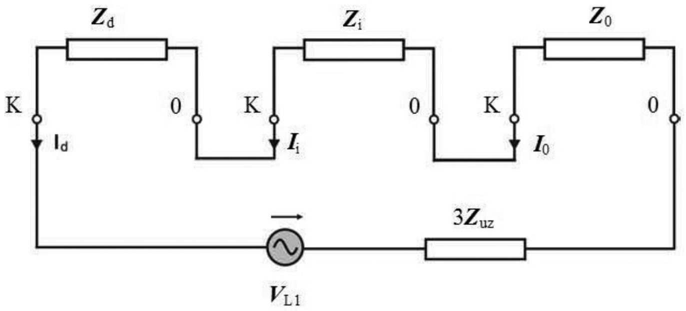
Slika 2 — Zemljospoj na srednjenaponskom nivou u TS SN/NN

Figure 2 — Ground fault at a the medium-voltage level in an MV/LV substation

Pretpostavlja se da je zemljospoj nastao u fazi L1. Kod izračuna struje zemljospoja (I_Z) koristit će se metoda superpozicije. Najprije će se u kratkospojnu vezu (K-D) zanemarivo malog otpora kojom teče struja zemljospoja ubaciti dva fiktivna međusobno suprotno orijentirana naponska izvora. Ovi naponi jednaki su faznom

Let us assume that the ground fault occurred in phase L1. The superposition method will be used in the ground fault current (I_Z) calculation. First of all, in the short-circuit connection, which has negligible low resistance through which the short-circuit current flows, two fictitious voltage sources of mutually opposite polarities are inserted. These voltages naponu koji je vladao na mjestu zemljospoja prije njegovog nastanka (V_{L1}). U skladu s metodom superpozicije može se sustav za vrijeme zemljospoja rastaviti na dva sustava. Jedan od njih je sustav koji je bio prije kvara, a drugi će biti nazvan fiktivnim sustavom. U fiktivnom sustavu egzistira samo fiktivni napon, dok su ostali naponski izvori premošteni, a strujni izvori, ako ih ima, odspojeni. Na osnovi napona na mjestu zemljospoja za vrijeme zemljospoja te struje kroz kratkospojnu vezu (struja zemljospoja) fiktivni sustav može se prikazati u sustavu simetričnih komponenata na način prikazan na slici 3.

are equal to the phase voltage that was present at the ground fault point prior to its occurrence (V_{L1}). According to the superposition method, the system during a ground fault may be divided into two systems. One of them is the system that existed before the fault occurred and the other will be called the fictitious system. In the fictitious system, there is only fictitious voltage, while the other voltage sources are short-circuited, while the current sources, if they exist, are disconnected. On the basis of the voltage at the ground fault point during the ground fault and the current through the short-circuited connection (ground fault current), the fictitious sytem can be presented in a system of symmetrical components as shown in Figure 3.



Slika 3 — Fiktivni sustav u sustavu simetričnih komponenata

Figure 3 — Fictitious system in a system of symmetrical components

Ovdje je:

Z_d — impedancija sustava gledano s mjesta zemljospoja u direktnom sustavu,

Z_i — impedancija sustava gledano s mjesta zemljospoja u inverznom sustavu,

Z_0 — impedancija sustava gledano s mjesta zemljospoja u nultom sustavu,

Z_{uz} — impedancija između točaka D i 0 (referentna os sustava ili referentna zemlja),

V_{L1} — fazni napon na mjestu zemljospoja neposredno prije nastanka zemljospoja (obično se uzima da je njegov iznos jednak nazivnoj vrijednosti s kutem 0° prema referentnoj osi).

Stvarne električne veličine (napon i struja) za vrijeme zemljospoja dobiju se superpozicijom vrijednosti u sustavu prije zemljospoja i u fiktivnom sustavu. Budući da prije nastanka zemljospoja nije bilo kratkospojne veze slijedi da je za određivanje struje zemljospoja dovoljan fiktivni sustav.

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$$\boldsymbol{I}_{\mathrm{d}} = \boldsymbol{I}_{\mathrm{i}} = \boldsymbol{I}_0 = \frac{\boldsymbol{V}_{\mathrm{L1}}}{\boldsymbol{Z}_{\mathrm{d}} + \boldsymbol{Z}_{\mathrm{i}} + \boldsymbol{Z}_0 + 3\boldsymbol{Z}_{\mathrm{uz}}} \quad . \tag{1}$$

Struja zemljospoja jednaka je:

The ground fault current is equal to:

$$\boldsymbol{I}_\mathrm{z} = \boldsymbol{I}_\mathrm{d} + \boldsymbol{I}_\mathrm{i} + \boldsymbol{I}_0 = 3\,\boldsymbol{I}_0 \ , \tag{2}$$

$$\boldsymbol{I}_\mathrm{z} = \frac{3\,\boldsymbol{V}_\mathrm{L1}}{\boldsymbol{Z}_\mathrm{d} + \boldsymbol{Z}_\mathrm{i} + \boldsymbol{Z}_0 + 3\,\boldsymbol{Z}_\mathrm{uz}} \ . \tag{3}$$

Budući da su impedancije uzdužnih grana mnogo manje od impedancija poprečnih grana elemenata sustava može se napisati da je:

Since the impedances of the longitudinal branches are much lower than the impedances of the transversal branches of the system elements, it is possible to write the following:

$$\boldsymbol{Z}_\mathrm{d} \langle\langle\, \boldsymbol{Z}_0 \ , \tag{4}$$

$$\boldsymbol{Z}_\mathrm{i} \langle\langle\, \boldsymbol{Z}_0 \ . \tag{5}$$

Nadalje, uz sljedeće pretpostavke:

Furthermore, under the following assumptions:

$$\boldsymbol{Z}_\mathrm{d} \approx 0 + \mathrm{j}\,0 \ , \tag{6}$$

$$\boldsymbol{Z}_\mathrm{i} \approx 0 + \mathrm{j}\,0 \ , \tag{7}$$

$$\boldsymbol{Z}_0 = 0 + \frac{1}{\mathrm{j}2\pi f\, C_\mathrm{z}} \ , \tag{8}$$

$$\boldsymbol{Z}_\mathrm{uz} \approx 0 + \mathrm{j}\,0 \ , \tag{9}$$

gdje je:

C_Z — dozemni kapacitet mreže srednjeg napona u kojoj se desio zemljospoj,
f — frekvencija,

dobije se prema [1] i [2] često korištena relacija za izračun struje zemljospoja koji se dogodio u fazi L3 (pri tom je smjer struje suprotan od onog prikazanog na slici 2):

where

C_Z — ground capacitance of the medium-voltage network in which the ground fault occurred,
f — frequency,

according to [1] and [2], a frequently used expression for the calculation of the ground fault current which occurred in Phase L3 is obtained (the direction of the current is opposite to that shown in Figure 2):

$$\boldsymbol{I}_\mathrm{z} = \frac{3\,(-\boldsymbol{V}_\mathrm{L3})}{\dfrac{1}{\mathrm{j}2\pi f\, C_\mathrm{z}}} \ , \tag{10}$$

$$\boldsymbol{I}_\mathrm{z} = \frac{3\,(-\mathrm{a}\,\boldsymbol{V}_\mathrm{L1})}{\dfrac{1}{\mathrm{j}\,2\pi f\, C_\mathrm{z}}} \ , \tag{11}$$

gdje je:

a — operator ($a = e^{j120°}$), pa vrijedi:

where

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$$\boldsymbol{I}_\mathrm{z} = 3\,\boldsymbol{V}_\mathrm{L1}\,2\pi f\, C_\mathrm{z}\, e^{\mathrm{j}30^o} \; . \tag{12}$$

Kod mreže srednjeg napona sa zračnim vodovima bez dozemnog užeta struja mjerodavna za određivanje potencijala nul-vodiča u mreži niskog napona (I_{ZZ}) za vrijeme zemljospoja je:

For a medium-voltage network with aerial cables lines without a grounding cable, the current used for determining the neutral conductor potential in a low-voltage network (I_{ZZ}) during a ground fault is as follows:

$$\boldsymbol{I}_\mathrm{zz} = \boldsymbol{I}_\mathrm{z} \; . \tag{13}$$

Prije je rečeno da mreža srednjeg napona može biti izvedena kabelskim vodovima. U tom slučaju s aspekta uzemljenja metalnih plašteva kabela može se javiti nekoliko slučajeva koji su relevantni za određivanje struje mjerodavne za određivanje potencijala nul-vodiča u mreži niskog napona (I_{ZZ}) za vrijeme zemljospoja. U osnovi postoje dvije grupe kabela i to:

— kabeli koji nemaju metalni plašt,
— kabeli koji imaju metalni plašt.

Pri tom metalni plaštevi kabela mogu biti:

— uzemljeni na oba kraja kabelskog voda,
— uzemljeni na jednom kraju kabelskog voda.

Ako je promatrani kabel uzemljen samo na jednom kraju, tada se razlikuju dva slučaja zemljospoja:

— zemljospoj nastao na mjestu u trafostanici koje je galvanski vezano za metalni plašt kabela i uzemljivački sustav trafostanice ili
— zemljospoj nastao na mjestu koje je galvanski vezano samo za uzemljivački sustav trafostanice (metalni plašt kabela na ovom mjestu nije uzemljen).

Postupak izračuna struje zemljospoja u slučaju kabela bez metalnog plašta i u slučaju kabela s metalnim plaštem kada zemljospoj nastane u TS SN/NN u kojoj nisu metalni plaštevi kabela vezani na uzemljivački sustav trafostanice, dok su na drugom kraju vezani, isti je prije prikazanom. Pri tom je važno napomenuti da u ovom slučaju impedancija Z_uz predstavlja ekvivalentnu impedanciju svih vlastitih i međusobnih impedancija elemenata sustava vezanih na uzemljivačke sustave mreža srednjeg i niskog napona (slika 2). Izračunata struja zemljospoja mjerodavna je za

It was previously stated that a medium-voltage network can use cable lines. In this case, from the aspect of the grounded metal cable sheaths, several relevant cases can occur for determining the current for the determination of the neutral-line conductor potential in a low-voltage network (I_{ZZ}) during a ground fault. Basically, there are two groups of cables, as follows:

— cables that do not have a metal sheath,
— cables that have a metal sheath.

Metal cable sheaths can be as follows:

— grounded at both ends of the cable line,
— grounded at one end of the cable line.

If a cable is grounded only at one end, two cases of ground fault can be differentiated:

— the ground fault occurred at a point in a substation which was galvanically connected to the metal cable sheath and the grounding system of the substation, or
— the ground fault occurred at a point that is only galvanically connected to the grounding system of the substation (the metal cable sheath is not grounded at this point).

The procedure for the calculation of the ground fault current in the case of a cable without a metal sheath and in the case of a cable with a metal sheath when a ground fault occurs in an MV/LV substation in which the metal cable sheaths are not connected to the grounding system of the substation, while they are connected at the other end, is the same as previously presented. It is important to note that in this case impedance Z_uz represents the equivalent impedance of all the self and mutual impedances of the system elements connected to the grounding systems of the medium-voltage and low-voltage određivanje potencijala nul-vodiča u mreži niskog napona.

U slučaju uzemljenja metalnih plašteva kabela na oba kraja jedan dio struje zemljospoja teći će plaštem, dok će drugi dio teći elementima koji su vezani na uzemljivački sustav i relevantni su za potencijal nul-vodiča [3], [4] i [5].

U slučaju kabelske mreže srednjeg napona utjecaj uzemljivačkih užadi kabela spojenih na uzemljivački sustav promatrane TS SN/NN uzima se u skladu s njihovim elektromagnetskim spregama s ostalim vodičima i pripadnim odvodima [3], [4], [5], [6], [7], [8] i [9].

3 PRORAČUN NAPONA NUL-VODIČA

Promatrajući zemljospoj na slici 2 vidljivo je da će u slučaju nesimetričnog opterećenja duž izvoda niskog napona i zemljospoja na srednjem naponu u pojnoj TS SN/NN teći struje kroz dijelove postrojenja povezane s uzemljivačkim sustavom i pri tom utjecati na napon (potencijal) nul-vodiča. Pod pojmom napona podrazumijeva se napon između neke točke na nul-vodiču i referentne osi (referentne zemlje). Analiza napona nul-vodiča provest će se metodom superpozicije. U skladu s ovom metodom sustav za vrijeme zemljospoja može se rastaviti na dva sustava. Jedan sustav će biti sa sekundarnim namotima transformatora kao naponskim izvorima (ekvivalent s elektromotornim silama i pripadnim impedancijama) i bez struje zemljospoja (stanje prije kvara), a drugi će biti s fiktivnim naponskim izvorom u kratkospojnoj vezi kojim teče struja zemljospoja i premoštenim elektromotornim silama prije spomenutog stvarnog naponskog izvora. Stvarne električne veličine dobiju se zbrajanjem njihovih vrijednosti u jednom i drugom sustavu. Dakle, da bi se odredio utjecaj struje zemljospoja na razini srednjeg napona u pojnoj TS SN/NN na napon nul-vodiča dovoljan je drugi sustav. Najveći napon nul-vodiča bit će u slučaju praznog hoda (neopterećene) mreže niskog napona.

3.1 Teorijske osnove

3.1.1 Zračni izvod niskog napona

Na slici 4 prikazana je TS SN/NN kojoj je na strani niskog napona priključen samo jedan zračni izvod. Postupak je sličan i u slučaju više izvoda niskog napona. Radi pojednostavljenja pretpostavlja se da duž trase voda niskog napona nema priključenih potrošača s pripadnim trošilima, odnosno da je mreža niskog napona u praznom hodu. Nadalje se pretpostavlja da svaki stup zračnog izvoda niskog napona ima

networks (Figure 2). The calculated ground fault current is applicable for the determination of the neutral conductor potential in a low-voltage network.

In the case of metal cable sheaths grounded at both ends, one part of the ground fault current will flow through the sheath while the other part will flow through the elements that are connected to the grounding system and relevant for the neutral conductor potential [3], [4] and [5].

In the case of a medium-voltage cable network, the influence of the grounding cables connected to the grounding system of the MV/LV substation is considered according to their electromagnetic coupling to other conductors and the corresponding output feeders [3], [4], [5], [6], [7], [8] and [9].

3 CALCULATION OF THE NEUTRAL CONDUCTOR VOLTAGE

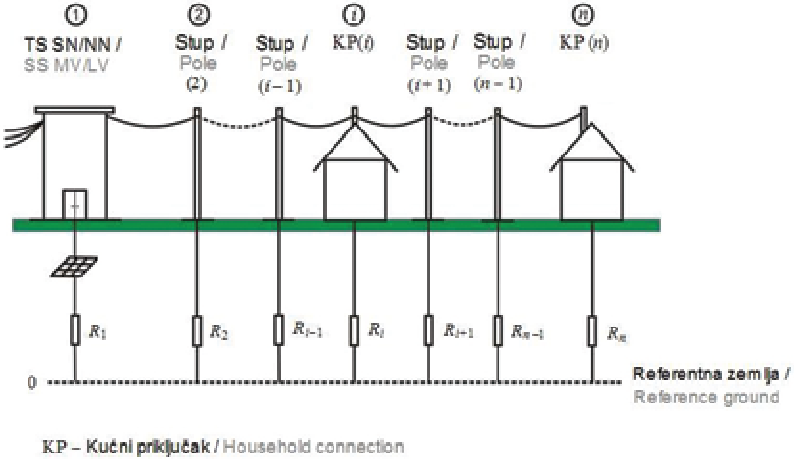
From the ground fault in Figure 2, it is evident that in the case of an asymmetrical load along the low-voltage feeder and ground fault at medium-voltage in an MV/LV supply substation, current will flow through the parts of the equipment connected to the grounding system and thus influence the voltage (potential) of the neutral conductor. The term voltage is understood to mean the voltage between a point on the neutral conductor and the reference axis (reference ground). Analysis of the neutral conductor voltage will be performed by the superposition method. According to this method, the system during a ground fault can be divided into two systems. One system will have secondary windings of the transformer as voltage sources (equivalent to electromotive forces and the corresponding impedances) and without ground fault current (the state prior to the fault), and the other will have a fictitious voltage source in a short-circuit connection through which ground fault current flows and short-circuited electromotive forces of the previously mentioned actual voltage source. The actual electrical values are obtained as the sum of the values in both systems. Therefore, the second system is sufficient in order to determine the influence of the ground fault current at the medium-voltage level in a supply MV/LV substation upon the neutral conductor voltage. The highest neutral conductor voltage will occur in the case of the no-load operation of a low-voltage network.

3.1 Theoretical foundations

3.1.1 Load voltage aerial feeder

In Figure 4, an MV/LV substation is presented to which only one aerial feeder is connected at the low-voltage level. The procedure is similar in the case of several low-voltage feeders. In order to simplify presentation, let it be assumed that there are no customers with their corresponding loads connected along the low-svoj uzemljivač karakteriziran pripadnim otporom. Cilj proračuna je odrediti napon nulvodiča duž trase izvoda niskog napona za vrijeme zemljospoja na razini srednjeg napona u pripadnoj TS SN/NN.

voltage line, i.e. the low-voltage network is in no-load operation. Furthermore, it is assumed that each pole of the low-voltage aerial feeder has its own grounding electrode and the corresponding grounding resistance. The goal of the calculation is to determine the neutral conductor voltage along the low-voltage feeder during a ground fault at the medium-voltage level in the corresponding MV/LV substation.



Slika 4 — Zračni izvod niskog napona iz TS SN/NN

Figure 4 — Low-voltage aerial feeder from an MV/LV

gdje je:

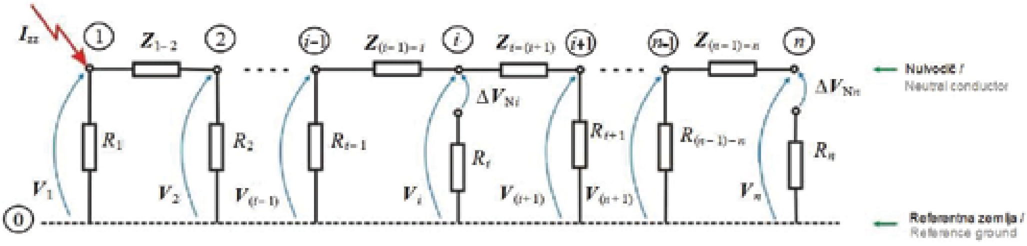
R_1 — otpor uzemljivača TS SN/NN,
R_2,..., R_{i-1} ,..., R_{i+1},..., R_{n-1} — otpor uzemljivača stupa,
R_i, R_n — otpor uzemljivača potrošača.

Na slici 5 prikazana je ekvivalentna shema ovakvog sustava u slučaju zemljospoja na razini srednjeg napona u promatranoj TS SN/NN. Budući da se analizira slučaj praznog hoda mreže niskog napona (neopterećena mreža), promatra se samo nul-vodič s pripadnim uzemljivačima trafostanice, stupova i kućnih priključaka (KP).

where

R_1 — grounding resistance of an MV/LV substation,
R_2,..., R_{i-1} ,..., R_{i+1},..., R_{n-1} — pole grounding resistance, and
R_i, R_n — grounding resistance of a customer facility.

In Figure 5, an equivalent diagram is presented of such a system in the event of a ground fault at the medium-voltage level in an MV/LV substation. Since no-load operation of the low-voltage network is analyzed, only the neutral conductor with the corresponding grounding electrodes of the substation, poles and household connections are considered.



Slika 5 — Ekvivalentna shema zračnog izvoda niskog napona u slučaju zemljospoja u TS SN/NN

Figure 5 — Equivalent diagram of a low-voltage aerial feeder in the event of a ground fault in an MV/LV substation

Prema Carsonu [1], [10] i [11] uzdužna impedancija $Z_{i\text{-}j}$ jednaka je:

According to Carson [1], [10] and [11], longitudinal impedance $Z_{i\text{-}j}$ equals:

$$\boldsymbol{Z}_{\mathrm{v}1} = R_{\mathrm{v}1} + \frac{\omega\,\mu_0}{8} + \mathrm{j}\,\frac{\omega\,\mu_0}{2\,\pi}\,\ln\left(\frac{658}{r'}\sqrt{\frac{\rho}{f}}\right), \tag{14}$$

$$\boldsymbol{Z}_{i-j} = \boldsymbol{Z}_{\mathrm{v}1} \cdot l_{i-j}\ . \tag{15}$$

Oznake su :

$R_{\mathrm{v}1}$ — radni otpor nul-vodiča po jedinici duljine,
$Z_{\mathrm{v}1}$ — uzdužna impedancija nul-vodiča po jedinici duljine,
$l_{i\text{-}j}$ — duljina dionice *i-j* nul-vodiča,
ω — kružna frekvencija, $\omega = 2\pi f$,
f — frekvencija,
μ_0 — magnetska permeabilnost vakuma,
ρ — specifični električni otpor (električna otpornost) tla,
r' — reducirani polumjer vodiča (nul-vodiča),
R_i — otpor i-tog uzemljivača (izmjeren ili izračunat).

Za mrežu sa slike 5 može se napisati sljedeća matrična jednadžba za određivanje napona nul-vodiča.

where

$R_{\mathrm{v}1}$ — the active resistance of the neutral conductor per unit of length,
$Z_{\mathrm{v}1}$ — the longitudinal impedance of the neutral conductor per unit of length,
$l_{i\text{-}j}$ — section length *i-j* of the neutral conductor,
ω — angular frequency, $\omega = 2\pi f$,
f — frequency,
μ_0 — magnetic permeability of vacuum,
ρ — specific soil resistivity,
r' — reduced conductor radius (neutral conductor),
R_i — i-th grounding resistance (measured or calculated).

For the network from Figure 5, it is possible to write the following matrix equation for the determination of the neutral conductor voltage:

$$\begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_i \\ \vdots \\ V_n \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1i} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2i} & \cdots & Y_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ Y_{i1} & Y_{i2} & \cdots & Y_{ii} & \cdots & Y_{in} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{ni} & \cdots & Y_{nn} \end{bmatrix}^{-1} \cdot \begin{bmatrix} I_{\mathrm{zz}} \\ 0 \\ \vdots \\ 0 \\ \vdots \\ 0 \end{bmatrix}, \tag{16}$$

gdje je:

Y_{ii} — vlastita admitancija *i*-tog čvora, $i = 1, 2, \dots, n$
Y_{ij} — međusobna admitancija *i*-tog i *j*-tog čvora, $i = 1, 2, \dots, n;\ j = 1, 2, \dots, \mathrm{n};\ i \neq j.$

Napon *i*-tog mjesta na nul-vodiču jednak je:

where

Y_{ii} — self admittance of the i-th note, $i = 1, 2, \dots, n$
Y_{ij} — mutual admittance of the *i*-th and *j*-th nodes, $i = 1, 2, \dots, n;\ j = 1, 2, \dots, \mathrm{n};\ i \neq j..$

The voltage of the i-th point on the neutral conductor equals:

$$\boldsymbol{V}_{\mathrm{N}i} = \boldsymbol{V}_i\ , \qquad i = 1, 2, \dots, n. \tag{17}$$

Napon između nul-vodiča i vlastitog uzemljivača u objektu i-tog potrošača (slika 5) jednak je:

The voltage between the neutral conductor and the grounding electrode of the facility of the i-th customer (Figure 5) equals:

$$\Delta V_{Ni} = V_{Ni} \ . \qquad (18)$$

3.1.2 Kabelski izvod niskog napona

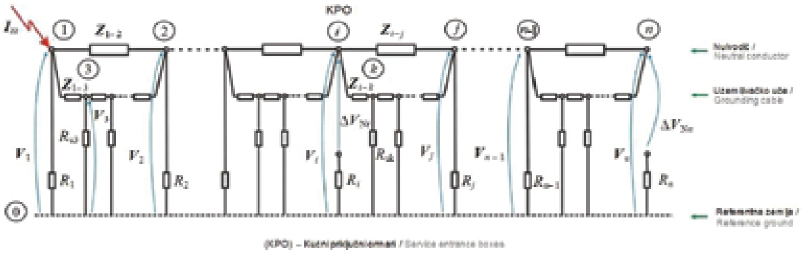
Na slici 6 prikazana je TS SN/NN kojoj je na strani niskog napona priključen samo jedan kabelski izvod. Sličan postupak je i u slučaju više izvoda. Radi pojednostavljenja, kao i kod zračnog izvoda pretpostavljeno je da duž trase voda niskog napona nema priključenih potrošača s pripadnim trošilima, odnosno da je mreža niskog napona u praznom hodu.

Nadalje se pretpostavlja da svaki kabelski ormarić na kabelskom izvodu niskog napona ima svoj uzemljivač karakteriziran pripadnim otporom. Na slici 6 prikazana je ekvivalentna shema sustava za izračun napona nul-vodiča u slučaju zemljospoja na razini srednjeg napona u promatranoj TS SN/NN. Budući da se analizira slučaj praznog hoda mreže niskog napona (neopterećena mreža), promatra se samo nul-vodič, uzemljivačka užad ili trake, uzemljivači kabelskih razvodnih ormara (KRO) i uzemljivači potrošača (kućni priključni ormari (KPO)).

3.1.2 Low-voltage cable feeder

In Figure 6, an MV/LV substation is presented to which only one cable feeder is connected on the low-voltage side. The procedure is similar in the case of several feeders. For the purpose of simplification, as with the aerial feeder, it is assumed that there are no customers with their corresponding loads connected along the low-voltage line, i.e. the low-voltage network is under no-load operation.

Furthermore, it is assumed that every cable box on the low-voltage cable feeder has its own grounding electrode characterized by the corresponding resistance. In Figure 6, an equivalent system diagram is presented for the calculation of neutral conductor voltage in the case of a ground fault at the medium-voltage level in an MV/LV substation. Since the no-load operation of a low-voltage network is analyzed, only the neutral conductor, grounding cables or strips, the grounding electrodes of the cable distribution boxes and the grounding electrodes of the customer facilities (service entrance boxes) are taken into account.



Slika 6 — Ekvivalentna shema kabelskog izvoda niskog napona u slučaju zemljospoja u TS SN/NN

Figure 6 — Equivalent diagram of a low-voltage cable feeder in the case of a ground fault in an MV/LV substation

Uzdužne impedancije grana računaju se prema izrazima (14) i (15). Pri tom je $l_{i\text{-}j}$ u slučaju nul-vodiča duljina dionice, dok je u slučaju uzemljivačkog užeta duljina $i\Delta$-tog segmenta Δl_{ui}. Budući da je uzemljivačko uže unutar dionice prikazano pomoću lanca T shema, za početnu i krajnju uzdužnu impedanciju unutar dionice uzima se duljina $\frac{\Delta l_{ui}}{2}$.

Otpor poprečne grane i-tog segmenta uzemljivačkog užeta duljine Δl_{ui} može se izračunti pomoću sljedećeg izraza [11]:

Longitudinal branch impedance values are calculated according to expressions (14) and (15). The section length of the neutral conductor is $l_{i\text{-}j}$ while in the case of the grounding cable the length of the i-th segment is Δl_{ui}. Since the grounding cable within the section is presented using a series of T circuits, for the first and last longitudinal impedance within a section, the length $\frac{\Delta l_{ui}}{2}$ is taken.

The resistance of the transversal branch of the i-th segment of the grounding cable of the length Δl_{ui} can be calculated using the following expression [11]:

$$R_{ui} = \frac{\rho}{\pi \, \Delta l_{ui}} \ln \frac{\Delta l_{ui}}{\sqrt{2 \, H \, r_{ui}}} \ , \tag{19}$$

gdje je:

H — dubina ukopavanja uzemljivačkog užeta,
r_{ui} — polumjer uzemljivačkog užeta.

Na slici 6 otpor uzemljivača TS SN/NN označen je R_1, dok su otpori uzemljivača potrošača označeni R_i i R_n . Otpor uzemljivača KRO, ako postoji, označen je R_j, $j = 2, \ldots, (n-1), j \neq i$.

Nakon formiranja matrice vlastitih i međusobnih admitancija čvorova mreže prikazane na slici 6 može se odrediti napon nul-vodiča koristeći se izrazom (16).

Napon i-tog mjesta na nul-vodiču jednak je:

where

H — burial depth of the grounding cable,
r_{ui} — radius of the grounding cable.

In Figure 6, the grounding resistance of the MV/LV substation is R_1, while the grounding resistances of the customer facilities are R_i and R_n . The grounding resistance of the cable distribution box, if it exists, is R_j, $j = 2, \ldots, (n-1), j \neq i$.

After the formation of the matrix of self and mutual node admittances of the network shown in Figure 6, it is possible to determine the neutral conductor voltage using Expression (16).

The voltage of the i-th point on the neutral conductor equals:

$$\begin{gathered} \boldsymbol{V}_{\mathrm{N}i} = \boldsymbol{V}_i \ , \\ i = 1, 2, \ldots, n. \end{gathered} \tag{20}$$

Napon između nul-vodiča i vlastitog uzemljivača u objektu i-tog potrošača (slika 6) jednak je:

The voltage between the neutral conductor and the grounding electrode in the facility of the i-th customer (Figure 6) equals:

$$\Delta \boldsymbol{V}_{\mathrm{N}i} = \boldsymbol{V}_{\mathrm{N}i} \ . \tag{21}$$

4 NAPON NUL-VODIČA U REALNOJ MREŽI NISKOG NAPONA

Za primjer su odabrana dva segmenta distribucijske mreže DP Elektrodalmacija Split (TS 10(20)/0,4 kV Bračevići 4 i TS 10(20)/0,4 kV Krč) kod kojih su mreže 10(20) kV u pogonu s izoliranim zvjezdištima. Prva se napaja iz TS 35/10(20) kV Muć, a druga iz TS 35/10(20) kV Klis. Za obje je zajedničko da se njihove mreže 10 kV i 0,4 kV rasprostiru kraškim terenom s vrlo visokim specifičnim električnim otporom tla. TS 35/10(20) kV Muć instalirane snage 2 x 4 MVA ruralna je trafostanica koja pokriva široko područje bez većih gospodarskih aktivnosti. Trenutačno je u pogonu samo jedan transformator, dok je drugi u rezervi. Mreža 10(20) kV napajana iz ove trafostanice pretežno

4 NEUTRAL CONDUCTOR VOLTAGE IN AN ACTUAL LOW-VOLTAGE NETWORK

As an example, two segments of the distribution network DP Elektrodalmacija Split (the Bračevići 4 10(20)/0,4 kV substation and the Krč 10(20)/0,4 kV substation), for which the 10(20) kV networks are in operation with isolated neutral points, have been selected. The first is supplied from the Muć 35/10(20) kV substation and the second from the Klis 35/10(20) kV substation. Both their 10 kV and 0,4 kV networks extend into karstic terrain with high specific soil resistivity. The Muć 35/10(20) kV substation has an installed capacity of 2 x 4 MVA and is a rural substation that covers a broad area without major economic activity. Currently, only one transformer is in operation while the second is in reserve. The 10(20) kV network supplied from this substation is primarily aerial. The area je zračna. Područje napajano iz TS 35/10(20) kV Klis, instalirane snage 2 x 8 MVA, specifično je po iznimno brzom prirastu novih potrošača, u prvom redu zbog naglog širenja poduzetničke zone Podi, te zbog izgradnje auto-ceste Zagreb – Šestanovac. Mreža naponske razine 10(20) kV napajana iz ove trafostanice mješovitog je kabelsko-zračnog karaktera. Naime, svi novi izvodi su u pravilu kabelski, dok su stari izvodi zračni. Nagli razvoj ove mreže ima za posljedicu naglo povećanje struje zemljospoja. Razlog za odabir ove konkretne mreže je, pored ostalog i njena konfiguracija. U zoni Podi svi izvodi 10(20) kV i 0,4 kV izvedeni su isključivo kabelski. Okolna sela napajaju se zračnim vodovima 10(20) kV. Pored toga, izvodi 0,4 kV u ovim selima su isključivo zračni, izvedeni golim vodičima i samonosivim kabelskim snopom.

4.1 Struja zemljospoja

U ovom primjeru analizira se zemljospoj na naponskoj razini 10 kV u TS 10(20)/0,4 kV Bračevići 4, odnosno u TS 10(20)/0,4 kV Krč.

TS 10(20)/0,4 kV Bračevići 4

TS 10(20)/0,4 kV Bračevići 4 instalirane snage 250 kVA stupna je trafostanica (u daljnjem tekstu: STS) napajana zračnim vodom 10(20) kV iz TS 35/10(20) kV Muć, a njena mreža 0,4 kV sastoji se od tri SKS izvoda na drvenim i betonskim stupovima. Iznos struje zemljospoja na naponskoj razini 10 kV stupne trafostanice izračunat na modelu u skladu s jednadžbom (3) iznosi:

supplied from the Klis 35/10(20) kV substation has an installed capacity of 2 x 8 MVA and is characterized by an exceptionally rapid increase in the number of new customers, primarily due to the sudden expansion of the Podi entrepreneurial zone and the construction of the Zagreb – Šestanovac Highway. The 10(20) kV network supplied from this substation is of a mixed cable-aerial character. All the new feeders are as a rule cable, while the old feeders are aerial. The sudden development of this network has resulted in a sudden increase in the ground fault current. A reason for the selection of this specific network, among others, is its configuration. In the Podi zone, all the 10(20) kV and 0,4 kV feeders are cable feeders. The surrounding villages are supplied by 10(20) kV aerial lines. Moreover, the 0,4 kV feeders in these villages are all aerial, with bare conductors and bundled cables.

4.1 Ground fault current

In this example, a ground fault is analyzed at a voltage level of 10 kV at the Bračevići 4 10(20)/0,4 kV substation and the Krč 10(20)/0,4 kV substation.

Bračevići 4 10(20)/0,4 kV substation

The Bračevići 4 10(20)/0,4 kV substation, with an installed capacity of 250 kVA, is a pole substation supplied by a 10(20) kV aerial line from the Muć 35/10(20) kV substation. Its 0,4 kV network consists of three bundled cable feeders on wooden and concrete poles. The value of the ground fault current at the 10 kV voltage level of the pole substation calculated on the model according to Equation (3) is

$$I_z = 4{,}46\,\mathrm{A}\ . \qquad (23)$$

U tablici 1 prikazani su iznosi struja zemljospoja (I_z) dobiveni mjerenjem u vlažnom (19.5.2006. godine) i suhom razdoblju (4.7.2006. godine).

In Table 1, the ground fault currents (I_z) obtained by measurement in a rainy period (2006-05-19) and a dry period (2006-07-04) arre presented.

Tablica 1– Izmjereni iznos struje zemljospoja
Table 1– Measured ground fault current values

Redni broj / Ordinal Number	Mjesto zemljospoja (Mjerno mjesto) / Grount fault point (measurement site)	Konfiguracija mreže / Network configuration	Datum mjerenja / Date of measurement	
			2006-05-19	2006-07-04
			I_z [A]	I_z [A]
1	TS / SS 35/10(20) kV Muć (10 kV)	Cijela 10(20) kV mreža u pogonu / Entire 10(20) kV network in operation	4,2	4,1
2	STS / PSS 10(20)/0,4 kV Bračevići 4, (10 kV)	Spojeni uzemljivači cjelokupne mreže niskog napona priključene na STS / The grounding electrodes of the entire low-voltage network connected to the pole substation are bonded together.	3,53	3,4
3	STS / PSS 10(20)/0,4 kV Bračevići 4, (10 kV)	Odspojeni uzemljivači cjelokupne mreže niskog napona, priključen samo uzemljivač STS / The grounding electrodes of the entire low-voltage network are disconnected, and only the grounding electrode at the pole substation is connected.	3,3	3,2

Uspoređujući vrijednosti dobivene na modelu s mjerenjem uočavaju se neke razlike koje su rezultat nemogućnosti točnog izračunavanja dozemnih kapaciteta relevantnih elemenata mreže i nepoznavanja otpora dijela električnog kruga kojim teče struja zemljospoja.

TS 10(20)/0,4 kV Krč

TS 10(20)/0,4 kV Krč instalirane snage 630 kVA napaja se kabelskim vodom 10(20) kV iz TS 35/10(20) kV Klis. Kabelski vod izveden je s tri kabela 20 kV, tipa XHE 49-A, 1x150 mm^2, položenih u trolist. Iznos struje zemljospoja na naponskoj razini 10 kV trafostanice TS 10(20)/0,4 kV Krč izračunat na modelu u skladu s jednadžbom (3) iznosi:

Comparing the values obtained on the model with the measured values, several differences are noted resulting from the impossibility of the precise calculation of the ground capacitances of the relevant network elements and the unknown resistance of the part of the electrical circuit through which the ground fault current flows.

Krč 10(20)/0,4 kV substation

The Krč 10(20)/0,4 kV substation, 630 kVA installed capacity, is supplied by a 10(20) kV cable line from the Klis 35/10(20) kV substation. The calbe line has three 20 kV cables, Type XHE 49-A, 1x150 mm^2, in trefoil formation. The ground fault current value at the 10 kV voltage level of the Krč 10(20)/0,4 kV substation calculated using the model according to Equation (3) is:

$$I_z = 87{,}58 \text{ A} . \tag{24}$$

Izmjerena vrijednost ove struje dana je u tablici 2 za suhi (2006-09-07) i vlažni (2006-09-26) kraški teren.

The measured value of this current is given in Table 2 for dry (2006-09-07) and wet (2006-09-26) karstic terrain.

Tablica 2 – Izmjereni iznos struje zemljospoja
Table 2 – Measured ground fault current values

Datum mjerenja / Date of measurement	I_z [A]
2006-09-07	88,6
2006-09-26	87,5

4.2 Napon nul-vodiča zračnog izvoda niskog napona

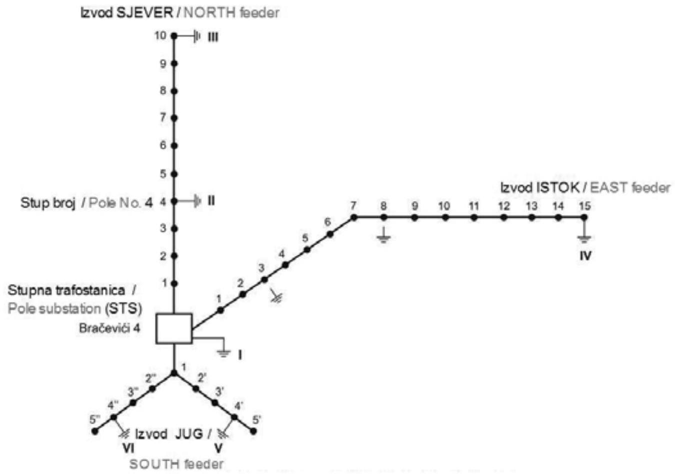
Odabrana je mreža niskog napona napajana iz STS 10(20)/0,4 kV Bračevići 4 iz razloga što je topološki jednostavna i napaja mali broj potrošača. STS 10(20)/0,4 kV Bračevići 4 je stupna trafostanica izgrađena tijekom devedesetih godina prošlog stoljeća. Napaja se zračnim vodom 10(20) kV iz TS 35/10(20) kV Muć, a njena mreža 0,4 kV sastoji se od tri zračna SKS izvoda na drvenim i betonskim stupovima kojima se mali zaseoci napajaju električnom energijom.

Budući da se analizirana distribucijska mreža nalazi na kraškom terenu, gdje specifični električni otpor zemlje znatno ovisi o vremenskim prilikama (padalinama), mjerenje otpora uzemljivača vršeno je u vlažnom (2006-05-19) i suhom razdoblju (2006-07-04). Na slici 7 prikazana je analizirana mreža niskog napona napajana iz STS 10(20)/0,4 kV Bračevići 4.

4.2 Neutral conductor voltage of a low-voltage aerial feeder

The low-voltage supply network from the Bračevići 4 10(20)/0,4 kV pole substation was selected because it is topologically simple and supplies a small number of customers. The Bračevići 4 10(20)/0,4 kV pole substation was built during the 1990s. It is supplied by a 10(20) kV aerial line from the Muć 10(20) kV substation. Its 0,4 kV network consists of three aerial feeders (bundled cables) on wood and concrete poles, via which small villages are supplied with electricity.

Since the distribution network analyzed is located on karstic terrain, where the specific soil resistivity significantly depends upon the weather (precipitation), grounding resistance was measured during a wet period (2006-05-19) and a dry period (2006-07-04). In Figure 7, the analyzed low-voltage network supplied by the Bračevići 4 10(20)/0,4 kV pole substation is presented.



Slika 7 — Mreža niskog napona napajana iz stupne TS 10(20)/0,4 kV Bračevići 4
Figure 7 — Low-voltage network supplied from the Bračevići 4 10(20)/0,4 kV pole substation

Prije početka mjerenja na realnoj mreži napravljene su opsežne pripreme. Snimljena je cijela mreža niskog napona i izvršena su premjeravanja svih relevantnih udaljenosti u mreži. Izvršena su mjerenja otpora svih uzemljivača koji se nalaze u navedenoj mreži (**I**, **II**, **III**, **IV**, **V** i **VI**), osim uzemljivača potrošača.

Otpor uzemljivača stupne TS 10(20)/0,4 kV Bračevići 4 (RU STS) za različite datume mjerenja prikazan je u tablici 3.

Extensive preparations were conducted prior to the beginning of the measurement of the actual network. Data on the entire low-voltage network were taken and measurements were performed of all the relevant distances in the network. Ground resistance measurements of all the grounding electrodes in the network (**I**, **II**, **III**, **IV**, **V** and **VI**) were performed, except for the customer grounding electrodes.

Grounding resistance of the Bračevići 4 10(20)/0,4 kV pole substation (RG PS) for various dates of measurement is shown in Table 3.

Tablica 3 – Izmjereni otpor uzemljivača STS
Table 3 – Measured grounding resistance of the pole substation

Oznaka / Designation	Uzemljivač I / Grounding electrode 1	
Datum mjerenja / Date of measurement	2006-05-19	2006-07-04
$R_{U\,STS}$ [Ω] / $R_{G\,PS}$	30,5	71,5

Bitno je napomenuti da su tijekom mjerenja otpora uzemljivača stupne trafostanice nulvodiči sva tri izvoda niskog napona odspojeni u stupnoj trafostanici kako bi se eliminirao utjecaj uzemljivača izvedenih duž trase voda niskog napona. Pored ovih podataka, izmjerene su relevantne udaljenosti po izvodima, također i otpor uzemljivača stupova duž trase voda niskog napona ($R_{U\ stupa}$). U tablici 4 prikazani su podaci za prvi izvod niskog napona (izvod SJEVER). Duljina raspona odnosi se na raspon koji prethodi dotičnom stupu, tako da je za prvi stup duljina raspona udaljenost od STS do prvog stupa. Također se vidi kod kojih stupova je nulvodič uzemljen (stupovi br. 4 i 10), a kod kojih nije (stupovi kod kojih nema upisanog podatka

It is important to note that during the measurement of the grounding resistance of the pole substation, the neutral conductors of all three low-voltage feeders were disconnected in the pole substation in order to eliminate the influence of the grounding electrodes installed along the low-voltage line. In addition to these data, the relevant distances for each feeder were measured, as well as the grounding resistance of the poles along the low-voltage line ($R_{G\ pole}$). In Table 4, data are presented for the first low-voltage feeder (NORTH feeder). The spacing length refers to the distance between a pole and the preceding pole, or in the case of the first pole the distance from the pole substation. It is also evident at which poles the neutral conductor is grounded (poles No. 4 and 10), and at which they are not (the poles for which there is no o otporu uzemljenja). U tablici 4 prikazani su izmjereni podaci za izvod niskog napona SJEVER.

data entered on the grounding resistance). In Table 4, measured data are presented for the low-voltage NORTH feeder.

Tablica 4 – Izvod niskog napona SJEVER
Table 4 – Low-voltage NORTH feeder

Broj stupa / Pole No.			1	2	3	4	5	6	7	8	9	10
Oznaka uzemljivača / Designation of grounding electrode						II						III
Duljina raspona / Spacing length			35	36	33	34	38	34	37	35	36	39
Datum mjerenja / Date of measurement	2006-05-19	RU stupa / RG pole [Ω]				63						34
	2006-07-04					170						50

U tablici 5 prikazani su izmjereni podaci za drugi izvod niskog napona (izvod ISTOK). Ovaj izvod napaja samo jednu kuću na kraju izvoda i izvod niskog napona izveden je na način da je SKS vod postavljen na stupove DV 10(20) kV. Stupovi br. 3, 8 i 15 su betonski s izvedenim uzemljivačima. Nul-vodič mreže niskog napona uzemljen je samo kod potrošača, tj. na stupnom mjestu br. 15. Otpori uzemljivača stupova koji nisu spojeni s nul-vodičem (stupovi br. 3 i 8) su podcrtani u tablici 5.

In Table 5, the measured data are presented from the second low-voltage feeder (EAST feeder). This feeder supplies only one house at the end of the feeder and the low-voltage feeder is installed in such a manner that the bundled cable line is supported by poles of the 10(20) kV distribution line. Poles No. 3, 8 and 15 are concrete and installed with grounding electrodes. The neutral conductor of the low-voltage network is grounded only in the customer's installation, i.e. at pole site No. 15. The grounding resistances of the poles that are not connected to the neutral conductor (Poles No. 3 and 8) are underlined in Table 5.

Tablica 5 – Izvod niskog napona ISTOK
Table 5 – Low-voltage EAST feeder

Broj stupa / Pole No.			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Oznaka uzemljivača / Designation of grounding electrode																	IV
Duljina raspona / Spacing length [m]			42	39	41	38	40	32	46	29	41	39	40	38	38	40	38
Datum mjerenja / Date of measure-ment	2006-05-19	RU stupa / RG pole [Ω]			**21**					**22**							**21**
	2006-07-04						**39**		**46**			**50**					**46**

Izmjereni podaci za treći izvod prikazani su u tablici 6. Iz navedenih podataka vidi se da se kod prvog stupa taj izvod dijeli na dva podizvoda koji napajaju dvije grupe potrošača.

The data measured for the third feeder are presented in Table 6. From these data, it is evident that for the first pole the feeder is divided into two subfeeders which supply two groups of customers.

Tablica 6 – Izvod niskog napona JUG
Table 6 – Low-voltage SOUTH feeder

Broj stupa / Pole No.			1	2'	3'	4'	5'	2''	3''	4''	5''
Oznaka uzemljivača / Designation of grounding electrode						V				VI	
Duljina raspona / Spacing length [m]			30	22	30	25	10	25	10	16	25
Datum mjerenja / Date of measurement [Ω]	2006-05-19	RU stupa / RG pole				16				20	
	2006-07-04					23				49	

Analizirajući prethodne tablice uočava se da se vrijednosti otpora uzemljivača znatno razlikuju

When analyzing the previous tables, it is evident that the values of the grounding resistance differ signifii da ovise o meteorološkim prilikama (vlažano ili suho razdoblje). S aspekta napona nul-vodiča nepovoljnija je situacija kada su otpori uzemljivača viši.

U skladu s tim, kod proračuna napona čvorišnih točaka na nul-vodiču stvarne mreže niskog napona priključene na stupnu TS 10(20)/0,4 kV Bračevići 4 uzeti su podaci od 2006-07-04. Analiza je provedena za sljedeće slučajeve:

- svi uzemljivači od **I** do **VI** su spojeni na nul-vodič,
- odspojen uzemljivač **II**,
- odspojen uzemljivač **III**,
- odspojeni uzemljivači **II** i **III**,
- odspojeni uzemljivači **II**, **III** i **VI**,
- odspojen uzemljivač **VI**,
- spojen samo uzemljivač STS (**I**), ostali odspojeni.

Izračunati iznosi napona nul-vodiča na mjestima **I**, **II**, **III**, **IV**, **V** i **VI** dani su u tablici 7.

cantly and that they depend upon the meteorological conditions (wet or dry period). From the aspect of the neutral conductor voltage, the situation is unfavorable when the grounding resistance is higher.

Therefore, in the calculation of the voltage of the node points on the neutral conductor of the actual low-voltage network connected to the Bračevići 4 10(20)/0,4 kV pole substation, data from 2006-07-04 are used. Analysis was performed for the following cases:

- all grounding electrodes from **I** to **VI** are connected to the neutral conductor,
- disconnected grounding electrode **II**,
- disconnected grounding electrode **III**,
- disconnected grounding electrodes **II** and **III**,
- disconnected grounding electrodes **II**, **III** and **VI**,
- disconnected grounding electrode **VI**,
- only the grounding electrode of the pole substation (**I**) is connected, the others are disconnected.

The calculated values for the neutral conductor voltage at points **I**, **II**, **III**, **IV**, **V** and VI are presented in Table 7.

Tablica 3 – Izmjereni otpor uzemljivača STS
Table 3 – Measured grounding resistance of the pole substation

Stanje mreže niskog napona / State of the low-voltage network	I_Z [A]	V_I [V]	V_{II} [V]	V_{III} [V]	V_{IV} [V]	V_V [V]	V_{VI} [V]
Spojeni svi uzemljivači mreže niskog napona / All grounding electrodes of the low-voltage network are connected	4,46	35,58	35,51	35,43	35,55	35,48	35,52
Odspojen uzemljivač II / Grounding electrode II is disconnected	4,46	37,32	37,28	37,19	37,29	37,22	37,27
Odspojen uzemljivač III / Grounding electrode III is disconnected	4,46	42,29	42,27	42,27	42,28	42,17	42,22
Odspojeni uzemljivači II i III / Grounding electrodes II and III are disconnected	4,46	44,75	44,75	44,75	44,75	44,63	44,69
Odspojeni uzemljivači II, III i VI / Grounding electrodes II, III and VI are disconnected	4,46	56,29	56,29	56,29	56,29	56,15	56,25
Odspojen uzemljivač VI / Grounding electrode VI is disconnected	4,46	42,48	42,40	42,30	42,47	42,37	42,44
Spojen samo uzemljivač STS (oznaka I), ostali uzemljivači II, III, IV, V i VI odspojeni / Only the grounding electrode of the pole substation (Designation I) is connected. The other grounding electrodes II, III, IV V and VI are disconnected.	4,46	311,2	311,2	311,2	311,2	311,2	311,2

Zbog minimiziranja troškova mjerenja, vodeći računa pri tom da se izmjerene vrijednosti mogu usporediti s izračunatim, mjerenje prije analiziranih napona nul-vodiča izvršeno je jednim instrumentom MI 2292 METREL koji ima šest kanala, tri za mjerenje struje i tri za mjerenje napona. U ovom slučaju korištena su tri ka-

In order to minimize measuring costs, taking into account that the measured values can be compared with the calculated values, measurement of the previously analyzed neutral conductor voltages was performed using an MI 2292 METREL instrument, which has six channels, three for measuring current and three for measuring voltage. In this case, the three nala za mjerenje napona na prije spomenutim mjestima, a jedan kanal za mjerenje struje zemljospoja. Rezultati ovih mjerenja dani su u tablici 8.

channels for measuring voltage were used at the aforementioned points, and one channel was used for measuring ground fault current. The results of these measurements are presented in Table 8.

Tablica 8 – Izmjereni iznosi napona nul-vodiča i struje zemljospoja u mreži niskog napona
Table 8 – Measured neutral conductor voltage and ground fault current values in the low-voltage network

Stanje mreže niskog napona / State of the low-voltage network	I_Z [A]	V_I [V]	V_{II} [V]	V_{III} [V]	V_{IV} [V]	V_V [V]	V_{VI} [V]
Spojeni svi uzemljivači mreže niskog napona / All the grounding electrodes of the low-voltage network are connected	3,4	25,1	25,0	24,9			25,0
Odspojen uzemljivač II / Grounding electrode II is disconnected	3,4	25,8		25,6			25,7
Odspojen uzemljivač III / Grounding electrode III is disconnected	3,4	26,5	26,4				26,3
Odspojeni uzemljivači II i III / Grounding electrodes II and III are disconnected	3,3	26,5					26,3
Odspojeni uzemljivači II, III i VI / Grounding electrodes II, III and VI are disconnected	3,3	28,4					
Odspojen uzemljivač VI / Grounding electrode VI is disconnected	3,3	26,2	26,1	26,1			
Spojen samo uzemljivač STS (oznaka I), ostali uzemljivači II, III, IV, V i VI odspojeni / Only the grounding electrode of the pole substation (Designation I) is connected. The other grounding electrodes II, III, IV V and VI are disconnected.	3,2	221,6					

Najveća izračunata vrijednost napona na modelu je 311,2 V, a najveća izmjerena vrijednost u realnoj mreži je 221,6 V i javlja se u slučaju kada su svi uzemljivači duž nul-vodiča bili odspojeni. Razlika se javlja zbog, kako je prije rečeno, nemogućnosti definiranja egzaktnog modela, tj. točnog izračunavanja dozemnih kapaciteta relevantnih elemenata mreže i nepoznavanja otpora dijela električnog kruga kojim teče struja zemljospoja. Ovaj iznos napona, koji u najgorem slučaju može biti napon dodira na nekom mjestu u mreži (ΔV_{Ni}), može biti opasan po život i zaštita od zemljospoja mora biti podešena tako da se eliminira ova opasnost. Iz svih predočenih rezultata zaključuje se da je sa stanovišta sigurnosti povoljnije da je nul-vodič uzemljen na što je god moguće više mjesta, naročito ako se radi o kraškom terenu.

4.3 Napon nul-vodiča kabelskog voda niskog napona

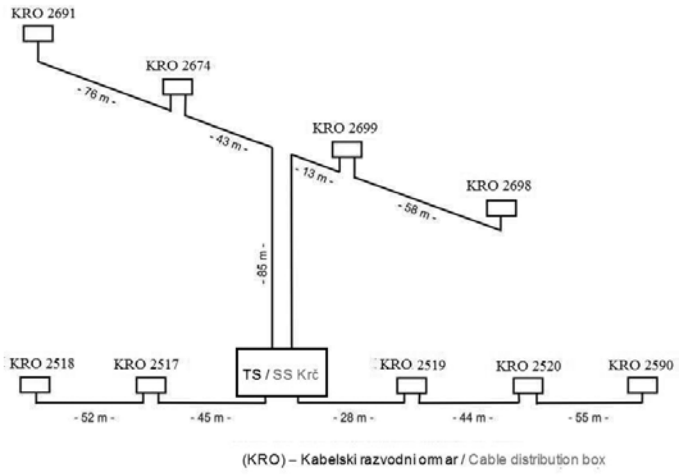
Posljednjih godina u gradovima se izvode isključivo kabelske, a u selima uz zračne sve više i kabelske mreže niskog napona. TS 10(20)/0,4 kV Krč nalazi se u gospodarskoj zoni Podi u Dugopolju. Mreža niskog napona trafostanice trenutačno se sastoji od 4 kabelska izvoda niskog napona kojima se napajaju gospodarski objekti u okolici trafostanice. Na slici 8 prikazana je jednopolna shema mreže niskog

The highest calculated voltage value using the model is 311,2 V, and the highest measured value in the actual network is 221,6 V, which occurred when all the grounding electrodes along the neutral conductor were disconnected. The difference occurs, as previously mentioned, due to the impossibility of defining an exact model, i.e. the precise calculation of the ground capacities of the relevant network elements and the unknown resistance of part of the electrical circuit through which the ground fault current flows. This voltage value, which in the worst case scenario can be touch voltage at a point on the network (ΔV_{Ni}), can be hazardous to life. Therefore, protection from ground faults should be adjusted in order to eliminate this danger. From all the results presented, it is concluded that from the safety standpoint it is better to ground the neutral conductor at as many points as possible, especially in karstic terrain.

4.3 Neutral conductor voltage of low voltage cable line

In recent years, exclusively low-voltage cable networks have been installed in cities, while in villages there are, together with aerial networks, an increasing number of low-voltage cable networks. The Krč 10(20)/0,4 kV substation is located in the Podi entrepreneurial zone in Dugopolje. The low-voltage substation network currently consists of 4 low-voltage cable feeders that supply commercial facilities in the surroundings of the substation. In Figure 8, a single-napona s duljinama pojedinih izvoda niskog napona. Svi kabeli niskog napona su tipa XP 00, 4x150 mm^2.

line diagram of the low-voltage network is presented with the lengths of individual low-voltage feeders. All the low-voltage cables are Type XP 00, 4x150 mm^2.



Slika 8 — Mreža niskog napona napajana iz TS 10(20)/0,4 kV Krč
Figure 8 — Low-voltage network supplied from the Krč 10(20)/0,4 kV substation

Mjerenje otpora uzemljivača trafostanice Krč izvedeno je uz odspojenu svu uzemljivačku užad položenu uz kabele niskog napona. Odspojeni su bili i svi nul-vodiči mreže niskog napona. Uzemljivačko uže uz dovodni kabelski vod srednjeg napona 10(20) kV nije bilo odspojeno od uzemljivača trafostanice, jer su bili potrebni značajni građevinski zahvati da bi se došlo do spojnog mjesta.

Radi toga je njegov utjecaj uzet u obzir kroz otpor uzemljivača same trafostanice [11]:

The measurement of the grounding resistance of the Krč substation was performed when all the grounding cables laid along the low-voltage cables were disconnected. All the neutral conductors of the low-voltage network were disconnected. The grounding cable along the medium-voltage 10(20) kV feeder cable was not disconnected from the grounding electrode of the substation because a significant construction undertaking would have been required to reach the connection point.

Therefore, its influence was taken into account through the grounding resistance of the substation [11]:

$$\boldsymbol{R}_{\mathrm{U\,TS/}} = 1{,}0\ \Omega\ . \qquad (24)$$

Kabelski vod srednjeg napona sastoji se od tri kabela 20 kV tipa XHE 49-A, 1x150 mm^2, položena u trolist. Uz pretpostavku da je specifični električni otpor zemlje jednak 1 000 Ωm izračunata je struja koja teče kroz uzemljivački sustav trafostanice za vrijeme zemljospoja [3] do [14]. Njen iznos je:

The medium-voltage cable line consists of three 20 kV cables, Type XHE 49-A, 1x150 mm^2, in trefoil formation. Assuming that the specific ground resistivity is equal to 1 000 Ωm, the current that flows through the grounding system of the substation during a ground fault is calculated [3] to [14]. Its value is:

$$\boldsymbol{I}_{\mathrm{zz}} = 28\ \mathrm{A}. \qquad (25)$$

Kabelski razvodni ormari duž pojedinih izvoda nisu uzemljeni.

The cable distribution boxes along individual feeders are not grounded.

Proračun napona nul-vodiča kabelske mreže niskog napona proveden je u skladu s poglavljem 3.1.2. U tablici 9 prikazane su neke od izračunatih vrijednosti. Pri tom su zbog usporedbe rezultata odabrane vrijednosti onih lokacija na kojima je izvršeno mjerenje.

Calculation of the neutral conductor voltage of the low-voltage cable network was conducted according to Chapter 3.1.2. In Table 9, several of the calculated values are presented. For the purpose of comparing results, values have been selected from those locations where measurement was conducted.

Tablica 9 – Izračunati iznosi napona nul-vodiča mreže niskog napona
Table 9 – Calculated values for the neutral conductor voltage of the low-voltage network

Lokacija / Location	TS / SS Krč /	KRO / Cable distribution box 2520	KRO / Cable distribution box 2590	KRO / Cable distribution box 2518
Napon nul-vodiča / Neutral conductor voltage	V_I [V]	V_{II} [V]	V_{III} [V]	V_{IV} [V]
	24,16	24,14	24,13	24,14

Mjerenje iznosa napona nul-vodiča u mreži niskog napona provedeno je na isti način kao u prethodnom poglavlju, tj. instrumentom MI 2292 METREL. Korištena su sva tri kanala za mjerenje napona na prije spomenutim mjestima. Rezultati ovih mjerenja prikazani su u tablici 10.

Measurement of the value of the neutral conductor voltage in the low-voltage network was conducted in the same manner as in the previous chapter, i.e. using the instrument MI 2292 METREL. All three channels were used for measuring the voltage at the aforementioned points. The results of these measurements are presented in Table 10.

Tablica 10 – Izmjereni iznosi napona nul-vodiča mreže niskog napona
Table 10 – Measured values for the neutral conductor voltage of the low-voltage network

Lokacija / Location		TS / SS Krč /	KRO / Cable distribution box 2520	KRO / Cable distribution box 2590	KRO / Cable distribution box 2518
Napon nul-vodiča / Neutral conductor voltage		V_I [V]	V_{II} [V]	V_{III} [V]	V_{IV} [V]
Datum mjerenja / Date of measurement	2006-09-07	18,4	17,9	17,7	18,3
	2006-09-26	12,6	12,2	12,0	12,6

Uspoređujući dobivene rezultate vidi se da su mjerene vrijednosti nešto niže od računskih. Razlog je između ostalog i u činjenici da mjerenje otpora uzemljivača nije bilo istog dana kada su bila mjerenja napona duž nul-vodiča nmreže niskog napona. Nadalje, neposredno pred mjerenje dana 2006-09-26 pala je obilna kiša koja je utjecala na smanjenje specifičnog otpora tla, a time i na izmjerene napone čvorova.

In comparing the results obtained, it is evident that the measured values are somewhat lower than the calculated values. One of the reasons is that measurement of the grounding resistance was not conducted on the same day as when the voltage was measured along the neutral conductor of the low-voltage network. Furthermore, immediately prior to measurement, on 2006-09-26 there was abundant rainfall which reduced the specific soil resistivity and thereby affected measured node voltages.

5 ZAKLJUČAK

Uzemljivački sustav mreže niskog napona direktno je povezan s uzemljivačkim sustavom trafostanice iz koje se napaja mreža niskog napona. Sa stanovišta sigurnosti ljudi najveća opasnost od napona dodira, u slučaju zemljospoja u mreži srednjeg napona s izoliranim zvjezdištem, javlja se kod zemljospoja u pojnoj trafostanici SN/NN, jer je u tom slučaju najviši

5 CONCLUSION

The grounding system of a low-voltage network is directly connected with the grounding system of the substation from which the low-voltage network is supplied. From the standpoint of human safety, the greatest hazard is from touch voltage, in the case of a ground fault in a medium-voltage network with an isolated neutral point, which occurs during a ground fault in a supply MV/LV substation, because in such potencijal na uzemljivaču trafostanice, koji se direktno preko nul-vodiča prenosi u instalacije potrošača.

Glavni elementi koji utječu na veličinu prenesenog potencijala u mrežu niskog napona su:

— tip mreže srednjeg napona (zračna, kabelska),
— otpor uzemljivača TS SN/NN, stupova mreže niskog napona, KRO i KPO,
— izvedba mreže niskog napona (zračna, kabelska).

Jedan od faktora koji utječe na iznos otpora uzemljenja je i specifični električni otpor tla. U slučajevima njegovih niskih vrijednosti lako je postići dovoljno nizak otpor uzemljivača TS SN/NN. Dok u slučaju njegovih visokih vrijednosti (kraški tereni) ni uz velika novčana ulaganja to nije uvijek lako ostvariti.

Kabelska mreža niskog napona u odnosu na zračnu ima prednost što se uza sve kabele niskog napona polaže uzemljivačko uže (traka). Zato je opasnost od pojave previsokih napona dodira u realnoj kabelskoj mreži minimalna. Kod zračne mreže niskog napona nul-vodič se uzemljuje na više mjesta, čime se povoljno djeluje na smanjenje iznosa napona nul-vodiča mreže niskog napona.

U ovom radu su analizirane dvije distribucijske mreže HEP ODS, DP Elektrodalmacija Split kod kojih su mreže 10(20) kV u pogonu s izoliranim zvjezdištima. Za obje je zajedničko da se njihove mreže 10 kV i 0,4 kV rasprostiru kraškim terenom s vrlo visokim specifičnim električnim otporom tla koji znatno ovisi o vremenskim prilikama (padalinama). Stoga je mjerenje otpora uzemljivača vršeno u vlažnom i suhom razdoblju. Paralelno s mjerenjima provedene su analize na računalnom modelu.

Provedena istraživanja pokazala su da se cjelokupan postupak određivanja napona nul-vodiča voda niskog napona u slučaju zemljospoja na razini srednjeg napona u pojnoj TS SN/NN može izvesti sa zadovoljavajućom točnošću pomoću odgovarajućeg modela na računalu.

Naime, odstupanje računskih rezultata od provedenih mjerenja dokazuje da je računski model na strani sigurnosti. To omogućava analiziranje najnepovoljnijih slučajeva koji se mogu pojaviti u realnoj mreži. Prezentirani rezultati istraživanja ukazuju na kontinuiranu potrebu ovakvih analiza da bi se ostvarila pravilna zaštita kod zemljospoja.

cases the highest potential on the grounding electrode of the substation is directly transferred via the neutral conductor to the customers' installations.

The main elements that influence the value of the transferred potential in a low-voltage network are as follows:

— the type of the medium-voltage network (aerial, cable),
— the grounding resistance of the MV/LV substation, low-voltage network poles, cable distribution boxes and service entrance boxes,
— the type of the low-voltage network (aerial, cable).

One of the factors that affects the grounding resistance value is specific soil resistivity. When this value is low, it is easy to achieve sufficiently low grounding resistance of an MV/LV substation, while when the value is high (karstic terrain), this is not always easy to achieve, even with considerable financial investment.

A low-voltage cable network has an advantage over an aerial network in that a grounding cable (strip) is laid along all the low-voltage cables. Therefore, the hazard from excessive touch voltage occurring in an actual cable network is minimal. In a low-voltage aerial network, the neutral conductor is grounded at several points, which reduces the value of the neutral conductor voltage of a low-voltage network..

In this article, two distribution networks of the HEP Distribution System Operator (HEP ODS), Distribution Region (DP) Elektrodalmacija Split are analyzed, in which the 10(20) kV networks have isolated neutral points. For both, their 10 kV and 0.4 kV networks extend through karstic terrain with high specific soil resistivity, which significantly depends upon the weather conditions (precipitation). Therefore, measurement of grounding resistance was performed during wet and dry periods. Parallel to the measurements, analyses were performed using a computer model.

These investigations have demonstrated that the entire procedure for the determination of the neutral conductor voltage of a low-voltage line in the case of a ground fault at the medium-voltage level in an MV/LV supply substation can be conducted with satisfactory precision using an appropriate computer model.

The differences between the calculated results and the measured results demonstrate that the computer model provides a higher margin of safety. This makes it possible to analyze the worst case scenarios that can occur in an actual network. The investigation results presented indicate that such analyses should be constantly conducted in order to achieve suitable protection from ground faults.

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Uredništvo primilo rukopis:
2008-03-11

Prihvaćeno:
2008-04-04

Manuscript received:
March 11, 2008

Accepted
April 4, 2008