UTJECAJNE VELIČINE NA DINAMIČKI ODZIV VERTIKALNOG CJEVASTOG UZEMLJIVAČA PRI IMPULSNOJ POBUDI

PARAMETERS AFFECTING THE TRANSIENT RESPONSE OF VERTICAL PIPE ELECTRODES TO IMPULSE EXCITATION

Tomislav Barić, Osijek , Hrvatska – Zijad Haznadar – Sead Berberović, Zagreb, Hrvatska

U radu je prikazana primjena teorije prijenosnih vodova pri analizi utjecaja različitih čimbenika na dinamički odziv uzemljivača. Radi jednostavnosti izlaganja te interpretacije dobivenih rezultata, a bez gubitka općenitosti, za uzemljivač je odabrana vertikalno ukopana cijev. Uzemljivač je spojen sa zemljovodom u čiji je gornji kraj idealnim strujnim izvorom utisnuta struja. Promjenom duljine zemljovoda analiziran je utjecaj geometrije iznad tla na dinamički odziv uzemljivača. Idealni strujni izvor generira strujni impuls normiranog valnog oblika tzv. dvostruko eksponencijalnog impulsa. Promjenom parametara valnog oblika struje analiziran je utjecaj kosine (ili strmine) čela vala na dinamički odziv uzemljivača. U radu je analiziran i utjecaj parametara tla na dinamički odziv uzemljivača. Tlo je modelirano kao jednoslojni homogeni izotropni poluprostor. Granica tlo-zrak predstavljena je ravninom. Dobiveni rezultati su prikazani grafički te diskutirani.
In this article, an application of the transmission line theory is presented for analyzing various parameters that affect the transient response of ground electrodes. In order to simplify the presentation and the interpretation of the results obtained, a vertical buried pipe electrode was chosen as the ground electrode. The ground electrode is connected to a grounding conductor, the upper part of which is connected to an ideal current source. The impact of the overhead geometry of the grounding conductor upon the transient response of the ground electrode is analyzed by varying the length of the grounding conductor. The ideal current source generates a normalized wave shape current impulse, a so-called double exponential impulse. The effect of the time to peak of the impulse (steepness of the rising edge of the peak current) on the transient response of the ground electrode is analyzed by varying the current wave shape parameters. The impact of soil parameters on the transient response of the ground electrode is also analyzed. The soil is modeled as a single-layer homogeneous isotropic semispace. The soil-air boundary is represented by a plane. The results obtained are presented graphically and discussed.

Ključne riječi: dinamički odziv, jednoslojno tlo, teorija prijenosnih vodova, vertikalni cjevasti uzemljivač
Key words: single soil layer, transient response, transmission line theory, vertical pipe electrode

1 UVOD

Pri atmosferskim pražnjenjima i/ili brzim sklopnim radnjama u elektroenergetskom sustavu, uzemljivač treba učinkovito odvesti u zemlju udarne struje vrlo velikih jakosti i vrlo strmog čela strujnih valova. Stoga je poznavanje elektromagnetskog dinamičkog odziva uzemljivača, odnosno njegovih dinamičkih parametara ključno za funkcioniranje i dimenzioniranje zaštite u elektroenergetskom postrojenju. Kako se strujno-naponske prilike pri dinamičkom odzivu uvelike razlikuju od onih pri stacionarnom odzivu na mrežnim frekvencijama (50/60 Hz), postupci za zaštitu od opasnih dodirnih napona i napona koraka koji vrijede za mrežne frekvencije teško su primjenjivi u slučaju kada je uzemljivač pobuđen impulsnom strujom. Iz tog razloga je prikladno na nekom jednostavnom primjeru uzemljivača, a koji se koristi u praksi analizirati čimbenike koji utječu na dinamički odziv uzemljivača pri impulsnoj pobudi. Pri tome valja imati na umu da osim čimbenika koji utječu na stacionarni odziv uzemljivača, na dinamički odziv uzemljivača pri impulsnoj pobudi djeluju dodatni čimbenici koji nemaju nikakav utjecaj na stacionarni odziv uzemljivača pri mrežnim frekvencijama. To su: parametri strujne pobude, smanjenje aktivne duljine vodiča, ionizacija tla u okolini uzemljivača, tlo koje prigušuje visoke frekvencije polja te **geometrija vodiča iznad tla**. Posebno valja istaći utjecaj geometrije vodiča iznad tla, jer se njezinim zanemarivanjem dobivaju i do dva puta povoljniji rezultati proračuna, što je **nedopustivo visoka pogreška u računu**. Upravo iz tog razloga analiziran je utjecaj nadzemne geometrije na odziv uzemljivača.

1 INTRODUCTION

During atmospheric discharges and/or fast switching in an electric power system, a ground electrode must effectively conduct the fast rise-time and high peak surge currents into the ground. Therefore, it is essential to know the characteristics of the transient electromagnetic response of the ground electrode, i.e. its transient parameters, in order to dimension (design) the elements of the grounding system in an electric power facility. Since current-voltage conditions differ greatly during transient response and stationary response at network frequencies (50/60 Hz), safety measures affording protection from dangerous touch and step voltages that are valid for network frequencies in the case of impulse current excitation are difficult to apply. For this reason, it is useful to analyze the factors that affect the transient response of a ground electrode during impulse excitation by taking a simple ground electrode used in practice as an example. It should be kept in mind that besides the parameters that influence the stationary response of a ground electrode, additional factors affect the transient response of the ground electrode to impulse excitation that have no effect whatsoever on the stationary response of the ground electrode at network frequencies. These are the parameters of current excitation, reduction in the active length of the conductors, ionization of the soil in the vicinity of the ground electrode, soil which attenuates high field frequencies and the **geometry of the overhead conductor**. The importance of the effect of the geometry of the overhead conductor should be emphasized because neglecting it can lead to results that are up to two times as favorable as the calculation results, **an unacceptably high error.** It is precisely for this reason that the effect of the overhead geometry on the ground electrode response is analyzed.

2 STRUJA GROMA I POBUDA UZEMLJIVAČA

Zbog stohastičke prirode udara groma dimenzioniranje uzemljivača temelji se na vjerojatnosnoj analizi. Važnija obilježja groma očitavaju se s grafikona ili iz tablica (tablica 1).

2 LIGHTNING STROKE CURRENT AND GROUND ELECTRODE EXCITATION

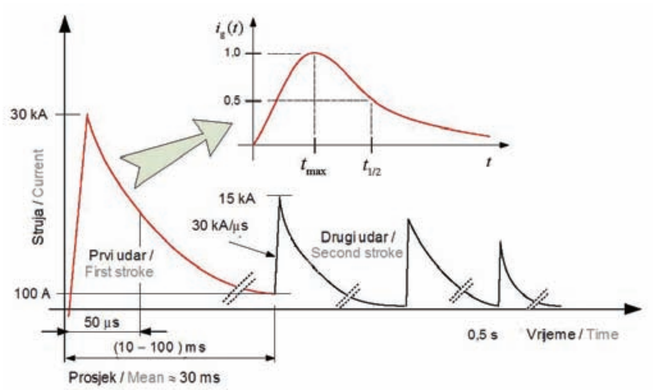
Due to the stochastic nature of a lightning strike, the dimensioning (design) of a ground electrode is based upon probability analysis. The significant characteristics of lightning strokes are presented in Table 1.

Tablica 1 — Osnovna obilježja gromova i njihova vjerojatnost prekoračenja [1]
Table 1 — Main characteristics of lightning strokes [1]

Vjerojatnost prekoračenja / Probability of exceeding	Amplituda / Peak current	Strmina čela vala / Rate of rise	$\int i^2 dt$	Trajanje / Total duration	Broj izbijanja / Number of discharges
P [%]	I [kA]	s [kA/μs]	[kA²s]	T[s]	n
50	26	48	0,54	0,09	1,8
10	73	74	1,9	0,56	5
1	180	97	35	2,7	12

Strmina strujnog vala (kosina prednjeg brida vala tj. čela vala) izravnog udara groma može doseći iznos od 100 kA/μs. Međutim, izravni udar groma je rijetko popraćen samo jednim strujnim impulsom, nego se redovito javlja nekoliko impulsa (pražnjenja) u razmaku od nekoliko desetaka milisekundi (slika 1 preuzeta iz [2]). Kako su parametri prvog udara znatno nepovoljniji od ostalih udara, za većinu primjena dovoljno je proračunski uvažiti samo prvi udar, što je i učinjeno u ovom radu. Prvi udar najčešće se aproksimira tzv. dvostruko eksponencijalnim valnim oblikom (manja slika na slici 1), koji je opisan vremenom čela t_{max} i vremenom začelja $t_{1/2}$.

The rate of rise of the peak current of a direct lightning stroke (steepness of the rising edge of the peak current) can reach a value of 100 kA/μs. However, a direct lightning strike is rarely accompanied by only one current impulse. Several impulses regularly occur (discharges or strokes) in an interval of several milliseconds (Figure 1, taken from Ref. [2]). Since the parameters of the first stroke are significantly less favorable than of the other strokes, for the majority of applications it is sufficient to take only the first stroke into account in calculations, as was the case in this article. The first stroke most often approximates the so-called double exponential wave shape (small illustration in Figure 1), which is described by the time to peak t_{max} and the time to half-value $t_{1/2}$.



Slika 1 — Valni oblik negativnog strujnog vala struje groma pri udaru zemlja-oblak
Figure 1 — Wave shape of negative ground/cloud lightning current

Vrijeme čela negativnog strujnog vala u prvom izbijanju prema [1] kreće se od 10 μs do 15 μs. Vrlo teški, a statistički rijetki udari groma imaju kraće vrijeme trajanja čela vala. U radu je za vrijeme začelja uzeto vrijeme od 50 μs. Za ovako usvojeno vrijeme začelja znatno različiti odzivi uzemljivača javljaju se pri promjeni vremena trajanja čela vala od 1 μs do 5 μs. Iz tog razloga je u radu promatran odziv uzemljivača na strujne impulse sljedećih oblika vala:

The negative current wave time to peak in the first discharge [1] ranges from 10 μs to 15 μs. Very powerful and statistically rare lightning strokes have shorter time to peak values. In the article, the time to half-value was assumed to be 50 μs. For this assumed value, significantly different ground electrode responses occur when the time to peak is changed from 1 μs to 5 μs. Therefore, in this article the ground electrode response to the current impulses of the following wave shapes were studied:

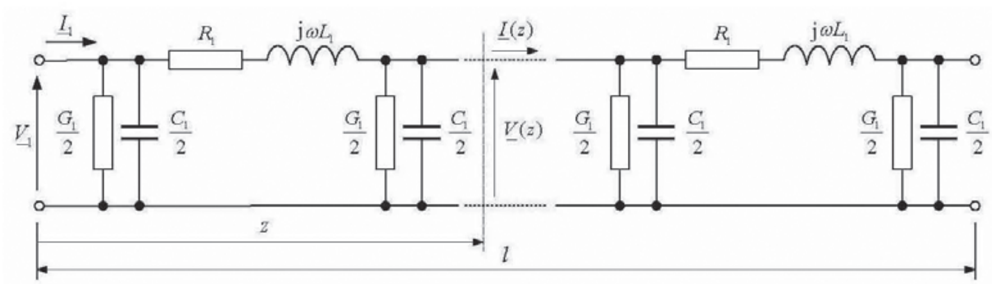
$$t_{max} / t_{1/2} = 1/50\ \mu s/\mu s\ ,\ t_{max} / t_{1/2} = 3/50\ \mu s/\mu s\ ,\ t_{max} / t_{1/2} = 5/50\ \mu s/\mu s\ .$$

3 FIZIKALNE POJAVE PRI ODVOĐENJU STRUJE IZ UZEMLJIVAČA

Ključna razlika između vođenja struje vodiča uzemljivača pri niskim i visokim frekvencijama iskazana je kroz pojavu smanjenja aktivne duljine uzemljivača. Navedenu pojavu najlakše je objasniti predstavljanjem cjevastog uzemljivača ekvivalentnim vodom u praznom hodu [3] slika 2.

3 PHYSICAL PHENOMENA DURING CURRENT DISCHARGE THROUGH A GROUND ELECTRODE

The crucial difference between the current flow through a grounding conductor at low and high frequencies is shown by decreasing the active length of the ground electrode. The easiest way to explain this phenomenon is by presenting a pipe electrode as an equivalent unloaded conductor [3] Figure 2.



Slika 2 – Ekvivalentni prijenosni vod, lanac „π" četveropola

Figure 2 – Equivalent transmission line, infinite series of „π" networks

Utisnuta struja $\underline{I}_1$ na početku voda nailazi na uzdužnu reaktanciju $j\omega L_1$, koja je pri niskim frekvencijama zanemariva te utisnuta struja niske frekvencije prolazi cijelom duljinom takvog uzemljivača. Porastom frekvencije raste i uzdužna reaktancija, koja joj otežava put ka preostaloj duljini prema kraju vodiča. Iz tog razloga najveći dio struje se odvodi u tlo na početnom dijelu vodiča uzemljivača gledano od točke utiskivanja struje. Preostali dio vodiča uzemljivača je neiskorišten, jer se iz njega mali dio struje odvodi u tlo. Iz tog razloga, za kvalitetno odvođenje struja visokih frekvencija, umjesto jednog dugog uzemljivača bolje je koristiti više kraćih uzemljivača. Pri odvođenju struja atmosferskih pražnjenja velikih jakosti vodiči uzemljivača poprimaju vrlo visoki električni potencijal što rezultira jakim električnim poljem oko vodiča uzemljivača. Posebno jako električno polje oko vodiča uzemljivača javlja se kada se on nalazi u loše vodljivom tlu. Električno polje koje se tada javlja katkada je veće od električne probojne čvrstoće tla i u okolišu uzemljivača nastupa električni proboj (kao korona kod vodiča u zraku). Ionizacija tla u ovom radu nije analizirana, a više o njoj može se naći u [4].

Injected current $\underline{I}_1$ encounters longitudinal reactance $j\omega L_1$ at the beginning of the line, which is negligible at low frequencies. Therefore, low frequency injected current flows through the whole length of such a ground electrode. With an increase in frequency, longitudinal reactance also increases, which impedes the path to the remaining length towards the end of the conductor. For this reason, most of the current is discharged into the soil at the beginning of the ground electrode, viewed from the current injection point. The remainder of the ground electrode is not used because only a small amount of current is discharged from it to the soil. Therefore, for the quality discharge of high frequency current, instead of one long ground electrode it is better to use several short ground electrodes. When high lightning stroke currents discharge into the ground through the buried part of a grounding conductor and a ground electrode, they acquire a very high potential, which results in a strong electric field around the grounding conductors. A particularly strong electric field around a grounding conductor occurs when it is located in poorly conducting soil. The electric field that occurs in such a case is sometimes greater than the electric breakdown strength of the soil and an electric arc occurs in the vicinity of the ground electrode (like a corona around the wire in the air). The ionization of the soil has not been analyzed in this article but further information is available in Ref. [4].

4 MATEMATIČKI POSTUPAK

Proračun odziva uzemljivača pobuđenog impulsnom strujom predstavlja vrlo složenu elektromagnetsku zadaću, koja se točno rješava jedino pomoću sustava Maxwellovih jednadžbi [5], [6]. S inženjerskog gledišta, modeli za analizu i prateći matematički postupci za proračun tranzijentnog odziva sustava uzemljenja trebaju biti jednostavni i brzi za primjenu, a istodobno moraju se predvidjeti sve važnije osobine dinamičkog (tranzijentnog) odziva. Trenutačno uporaba modela prijenosnih vodova ograničena je samo na uzemljivače jednostavne geometrije [7], kao što su prsteni ili ravne elektrode itd.. Uobičajeni postupak rješavanja dinamičkog odziva uzemljivača je da se primjenom Fourierove transformacije [8], [9] zadaća prebaci iz vremenskog područja u frekvencijsko područje u kojem se izvrši rješavanje za široki spektar harmoničkih funkcija koje opisuju zadanu ulaznu impulsnu struju, pa se zatim inverznom Fourierovom transformacijom sintetizira rješenje u vremenskom području [10]. Prebacivanje zadaće iz vremenskog područja u frekvencijsko područje obavlja se prema jednadžbi (1), a iz frekvencijskog područja natrag u vremensko područje prema jednadžbi (2):

4 MATHEMATICAL PROCEDURE

The calculation of the ground electrode response to the impulse current represents a highly complex electromagnetic task that can only be precisely solved using the system of Maxwell equations [5] and [6]. From the engineering viewpoint, the models for analysis and the corresponding mathematical procedures for the calculation of the transient response of a grounding system should be simple and quick to use, and at the same time they must anticipate all the important characteristics of the transient response. The currently used transmission line model is limited solely to ground electrodes with simple geometry [7], such as ring conductors or horizontal grounding wires etc. The customary procedure for solving the transient response of a ground electrode is that through the application of Fourier transformations, [8] and [9], the task is transferred from the time domain to the frequency domain in which the solution is performed for the broad spectrum of harmonic functions that describe the given input impulse current, and then by inverse Fourier transformation to synthesize the solution in the time domain [10]. Transferring the task from the time domain to the frequency domain is performed according to equation (1), and from the frequency domain back to the time domain according to equation (2):

$$\underline{V}_1(\mathrm{j}\omega) = \underline{Z}_{\mathrm{ul/in}}(\mathrm{j}\omega) \cdot \underline{I}(\mathrm{j}\omega)\ , \qquad (1)$$

$$v_1(t) = F^{-1}\left\{\left(\underline{Z}_{\mathrm{ul/in}}(\mathrm{j}\omega)\right)^* \cdot F\left\{i_1(t)\right\}\right\} \qquad (2)$$

gdje su F i F^{-1} Fourierova i inverzna Fourierova transformacija, a $V_1(\mathrm{j}\omega)$, $\underline{I}_1(\mathrm{j}\omega)$ i $\underline{Z}_{\mathrm{ul/in}}(\mathrm{j}\omega)$ Fourierovi transformati: napona, struje i ulazne valne impedancije.

where F and F^{-1} are Fourier and inverse Fourier transformations, and $V_1(\mathrm{j}\omega)$, $\underline{I}_1(\mathrm{j}\omega)$ and $\underline{Z}_{\mathrm{ul/in}}(\mathrm{j}\omega)$ are Fourier transforms: voltage, excitation current and input wave impedance.

5 VERTIKALNI CJEVASTI UZEMLJIVAČ

Kako se u ovom radu analizira vertikalno ukopani cjevasti uzemljivač, zbog njegove jednostavne geometrije umjesto složene teorije elektromagnetskog polja moguće je primijeniti znatno jednostavniju teoriju prijenosnih vodova [11]. Strujnonaponske prilike na ekvivalentnom vodu opisane su jednadžbama prijenosnih vodova [11]:

5 VERTICAL PIPE ELECTRODE

Since a vertical buried pipe electrode is analyzed in this article due to its simple geometry, it is possible to apply the significantly simpler transmission line theory instead of the complex electromagnetic field theory [11]. The current-voltage conditions at the equivalent line are described by the transmission line equations [11]:

$$\underline{V}(z) = \underline{V}_1 \cosh(\gamma z) - \underline{I}_1 \underline{Z}_C \sinh(\gamma z), \quad (3)$$

$$\underline{I}(z) = \underline{I}_1 \cosh(\gamma z) - \frac{\underline{V}_1}{\underline{Z}_C} \sinh(\gamma z), \quad (4)$$

gdje su:
$\underline{V}_1$ - napon na početku ekvivalentnog voda,
$\underline{I}_1$ - struja na početku ekvivalentnog voda,
γ - valna konstanta voda,
$\underline{Z}_C$ - karakteristična valna impedancija ekvivalentnog voda.

U izrazima (3) i (4) prostorna koordinata z mjeri se od kraja vodiča na kojega je narinut napon ili utisnuta struja prema slobodnom kraju vodiča. Valna impedancija $\underline{Z}_C$, voda prikazanog na slici 2, prema [11] određuje se izrazom:

where:
$\underline{V}_1$ - voltage at the beginning of the equivalent line,
$\underline{I}_1$ - current at the beginning of the equivalent line,
γ - propagation constant of the line , and
$\underline{Z}_C$ - characteristic wave impedance of the equivalent line.

In expressions (3) and (4), space coordinate z is measured from the end of the conductor to which the voltage is applied or the current is injected at the free end of the conductor. Wave impedance $\underline{Z}_C$, of the line shown in Figure 2, is determined by the following expression according to Ref. [11]:

$$\underline{Z}_C = \sqrt{\frac{\underline{Z}_1}{\underline{Y}_1}} = \sqrt{\frac{\underline{Z}}{\underline{Y}}} = \frac{\underline{Y}}{\gamma} \quad [\Omega], \quad (5)$$

gdje su:

$\gamma = \sqrt{\underline{Z}_1 \underline{Y}_1}$ valna konstanta (valni broj),
$\underline{Z}_1 = R_1 + j\omega L_1$ - jedinična uzdužna impedancija voda [Ω/m] u kojoj je
R_1 - jedinični uzdužni djelatni otpor voda [Ω/m],
L_1 - jedinični induktivitet voda [H/m],
$\underline{Y}_1 = G_1 + j\omega C_1$ - jedinična poprečna admitancija voda [S/m] u kojoj je
G_1 - jedinični poprečni odvod voda [S/m], a
C_1 - jedinični kapacitet voda [F/m].

Primarne konstante: R_1, L_1, G_1 i C_1 uzemljivača predstavljenog pomoću ekvivalentnog voda određuju se na jednak način kao i u slučaju nadzemnih vodova, tj. pod pretpostavkom kvazistatičkih uvjeta [11], uzimajući u obzir granicu tlo-zrak. Korekcija se obično vrši uvažavanjem površinskog učinka, tj. uvažavanjem unutarnje impedancije vodiča, što se odražava na određivanje uzdužne impedancije ekvivalentnog voda.

Karakteristična valna impedancija analiziranog ekvivalentnog voda jest:

where:

$\gamma = \sqrt{\underline{Z}_1 \underline{Y}_1}$ propagation constant (wave number),
$\underline{Z}_1 = R_1 + j\omega L_1$ - per unit longitudinal line impedance [Ω/m] in which
R_1 - per unit longitudinal active line resistance [Ω/m],
L_1 - per unit line inductance [H/m],
$\underline{Y}_1 = G_1 + j\omega C_1$ - per unit transversal line admittance [S/m] where
G_1 - per unit transverse line conductance, and
C_1 - per unit line capacitance [F/m].

The primary constants R_1, L_1, G_1 and C_1 of the ground electrode represented by the equivalent line are determined in the same way as in the case of overhead lines, i.e. under the assumption of quasistatic conditions [11], taking into account the soil-air boundary. Correction is generally performed by taking into account the surface effect, i.e. the internal impedance of the conductor, which is reflected in the determination of the longitudinal impedance of the equivalent line.

The characteristic wave impedance of the analyzed equivalent line is as follows:

$$\underline{Z}_C(f)=\sqrt{\frac{R_{1,DC}+\underline{Z}_{1,i}+j2\pi f L_1}{G_1+j2\pi f C_1}} \quad [\Omega], \tag{6}$$

gdje je:

$R_{1,DC}$ jedinični istosmjerni omski otpor, a

$\underline{Z}_{1,i}$ je jedinična unutarnja impedancija. Za cilindrični ravni vodič punog poprečnog presjeka vodljivosti κ_V, permeabilnosti μ_V i polumjera r pri frekvenciji f prema [12] ona iznosi:

where:

$R_{1,DC}$ is per unit direct current ohmic resistance, and

$\underline{Z}_{1,i}$ is per unit internal impedance. For a straight cylindrical conductor with a full cross section, conductivity κ_V, permeability μ_V and radius r at frequency f according to [12] is as follows:

$$\underline{Z}_{i,1}=\frac{1+j}{2\pi r}\sqrt{\frac{\pi f \mu_V}{\kappa_V}} \quad [\Omega/m], \tag{7}$$

Jedinični uzdužni induktivitet, s obzirom da s porastom frekvencije raste i prigušenje vala, određuje se korištenjem poznatih Pollaczek – Carsonovih teorijskih izraza [13]:

Per unit longitudinal inductance, since wave damping is also increased with increased frequency, is determined using the Pollaczek-Carson theoretical expressions [13]:

$$L_1=\left(1+2\ln\frac{2,24\sqrt{\rho}}{\sqrt{4\pi\omega\cdot 10^{-7}\cdot d}}\right)\cdot 10^{-7}-j\frac{\mu_0}{8} \quad [H/m], \tag{8}$$

gdje su:
d - promjer cilindričnog vodiča [m],
ρ - otpornost (specifični otpor) tla [Ωm],
ω - kružna frekvencija.

Ulazna valna impedancija u funkciji frekvencije uz zanemarenu geometriju iznad tla jest:

where:
d - diameter of the cylindrical conductor [m],
ρ - soil resistivity (specific resistance) [Ωm],
ω - angular frequency.

Input wave impedance as a function of frequency and ignoring the overhead geometry is as follows:

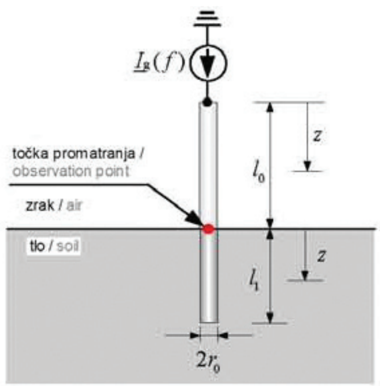
$$\underline{Z}_{ul/in}(f)=\underline{Z}_C(f)\cdot\coth\left(\gamma(f)l\right) \tag{9}$$

6 MODEL UZEMLJIVAČA S UKLJUČENOM GEOMETRIJOM IZNAD TLA

Polazeći od jednadžbi prijenosnih vodova (3) i (4) i primjenjujući ih na geometriju vodiča (prijenosnih vodova), koja se sastoji od vertikalnog cilindričnog voda iznad tla i vertikalno ukopanog cilindričnog vodiča, na način kako je to prikazano slikom 3, moguće je uvažiti istodobno refleksije od krajeva uzemljivača i krajeva vodiča iznad tla (što uključuje i granicu tlo-zrak).

6 GROUND ELECTRODE MODEL INCLUDING OVERHEAD GEOMETRY

Starting from the transmission line equations (3) and (4) and applying them to the geometry of the conductor (transmission lines) consisting of a vertical cylindrical overhead line and a vertical buried cylindrical conductor, as shown in Figure 3, it is possible to take the reflections from the ends of the ground electrode and the ends of the overhead conductor into account at the same time (which also includes the soil-air boundary).



Slika 3 — Sustav uzemljenja: uzemljivač-stup, i relevantna geometrija

Figure 3 — Grounding system: ground electrode-grounding conductor, and the relevant geometry

Sustav uzemljenja kojega čine uzemljivač i zemljovod (stup) prikazan na slici 3 može se opisati sustavom nelinearnih jednadžbi prijenosnih vodova. Pri tome su strujno-naponske prilike vodiča iznad tla (zemljovoda) opisane jednadžbama:

The grounding system consisting of a ground electrode and a grounding conductor shown in Figure 3 can be described by a system of nonlinear transmission line equations. The current-voltage conditions of the overhead conductor (grounding conductor) are described by the following equations:

$$\underline{V}_0(z) = \underline{V}_0 \mathrm{ch}(\gamma_0 z) - \underline{Z}_{c0}\underline{I}_0 \mathrm{sh}(\gamma_0 z) \ , \tag{10}$$

$$\underline{I}_0(z) = \underline{I}_0 \mathrm{ch}(\gamma_0 z) - \frac{\underline{V}_0}{\underline{Z}_{c0}} \mathrm{sh}(\gamma_0 z) \ . \tag{11}$$

u kojima se udaljenost z mjeri od točke utiskivanja struje (gornji kraj vodiča iznad tla) prema granici tlo-zrak (slika 3). Za vodič uzemljivača vrijede jednadžbe:

in which distance z is measured from the current injection point (upper end of the overhead conductor) toward the soil-air boundary (Figure 3). The following equation applies for the buried part of the grounding conductor (grounding electrode):

$$\underline{V}_1(z)=\underline{V}_1\mathrm{ch}(\gamma_1 z)-\underline{Z}_{c1}\underline{I}_1\mathrm{sh}(\gamma_1 z)\ , \tag{12}$$

$$\underline{I}_1(z)=\underline{I}_1\mathrm{ch}(\gamma_1 z)-\frac{\underline{V}_1}{\underline{Z}_{c1}}\mathrm{sh}(\gamma_1 z)\ . \tag{13}$$

u kojima se udaljenost z mjeri od granice tlo-zrak prema slobodnom kraju. Navedeni sustav jednadžbi (10) do (13) je potpun ukoliko su pravilno propisani rubni uvjeti kojima se povezuju oba vodiča i refleksije valova od granica. Napon na kraju zemljovoda u točki spajanja s uzemljivačem jednak je naponu na početku uzemljivača $\underline{V}_0(l_0)=\underline{V}_1(0)$. Struja na kraju zemljovoda u točki spajanja s uzemljivačem jednaka je struji na početku uzemljivača $\underline{I}_0(l_0)=\underline{I}_1(0)$. Struja na početku zemljovoda jednaka je struji strujnog izvora, tj. struji groma $\underline{I}_0(0)=\underline{I}_g$. Uzdužna struja uzemljivača na njegovom slobodnom kraju jednaka je nuli $\underline{I}_1(l_1)=0$. Uvrštavanjem navedenih rubnih uvjeta u jednadžbe (10) do (13) dobiva se:

in which distance z is measured from the soil-air boundary toward the free end. The system of equations (10) to (13) is complete if the boundary conditions are properly defined according to which both conductors and the wave reflection from the boundary are related. The voltage at the end of the grounding conductor at the connection point with the ground electrode is equal to the voltage at the beginning of the ground electrode $\underline{V}_0(l_0)=\underline{V}_1(0)$. The current at the end of the grounding conductor at the connection point with the ground electrode is equal to the current at the beginning of the ground electrode $\underline{I}_0(l_0)=\underline{I}_1(0)$. The current at the beginning of the grounding conductor is equal to the current of the current source, i.e. the stroke current $\underline{I}_0(0)=\underline{I}_g$. The longitudinal current of the ground electrode at its free end is equal to zero $\underline{I}_1(l_1)=0$. By entering the above border conditions into equations (10) to (13), the following is obtained:

$$\underline{V}_1=\underline{I}_g\frac{1}{\mathrm{ch}(\gamma_0 l_0)}\frac{\underline{Z}_{c0}\underline{Z}_{c1}}{\underline{Z}_{c0}\mathrm{th}(\gamma_1 l_1)+\underline{Z}_{c1}\mathrm{th}(\gamma_0 l_0)}\ . \tag{14}$$

Jednadžba (14) daje napon na kraju uzemljivača uz granicu tlo-zrak u funkciji pobudne struje $\underline{I}_g$, koja je utisnuta u vertikalni vodič na udaljenosti l_0 od granice tlo-zrak (slika 3). Jednadžba (14) odnosi se na monoharmonijsku pobudu. Iz tog razloga za potrebe određivanja vremenskog odziva potrebno je primijeniti inverznu Fourierovu transformaciju prema izrazu:

Equation (14) yields the voltage at the end of the ground electrode along the soil-air boundary as a function of excitation current $\underline{I}_g$, which is injected in the vertical conductor at a distance of l_0 from the soil-air boundary (Figure 3). Equation (14) refers to monoharmonic excitation. For this reason, in order to determine the time response, it is necessary to apply an inverse Fourier transformation, according to the following expression:

$$v_1(t)=F^{-1}\left\{F(i_g(t))\cdot\left(Z(\mathrm{j}\omega)\right)^*\right\}\ . \tag{15}$$

gdje je sa $Z(\mathrm{j}\omega)$ označena impedancija koja jest:

where $Z(\mathrm{j}\omega)$ is the impedance, as follows:

$$Z(\mathrm{j}\omega)=\frac{1}{\mathrm{ch}(\gamma_0 l_0)}\frac{\underline{Z}_{c0}\cdot\underline{Z}_{c1}(\mathrm{j}\omega)}{\underline{Z}_{c0}\mathrm{th}(\gamma_1(\mathrm{j}\omega)\cdot l_1)+\underline{Z}_{c1}(\mathrm{j}\omega)\mathrm{th}(\gamma_0\cdot l_0)}\ , \tag{16}$$

Na ovome mjestu važno je napomenuti da u izrazu (15) impedancija $Z(\mathrm{j}\omega)$ mora biti konjugirano

It is necessary to mention that in equation (15) impedance $Z(\mathrm{j}\omega)$ must be a conjugate complex kompleksna (teorem o konvoluciji [8] i [9]). U protivnom će napon $u_1(t)$ poprimiti nefizikalan oblik i iznos.

number (convolution theorem [8] and [9]). Otherwise, the voltage $u_1(t)$ will have a non-physical form and value.

7 DINAMIČKI ODZIV NA IMPULSNU POBUDU

Analiza impulsnog odziva samog uzemljivača nije dostatna već treba analizirati sustav uzemljenja, kojeg tvore uzemljivač, spojni vodovi, stupovi i vodiči sustava zaštite od groma [3]. Prilikom udara groma u sustav uzemljenja, strujni impuls groma pri svom kretanju prema uzemljivaču nailazi na promjene valne impedancije, što rezultira s refleksijama vala [11].

Kako je geometrija konačnih dimenzija, javljaju se višestruke refleksije koje je potrebno uzimati u obzir pri ispravnom određivanju odziva sustava uzemljenja i dimenzioniranju zaštite. Za potrebe teorijskih razmatranja, potrebno je pronaći najjednostavniji mogući model pomoću kojega je moguće kvalitativno i kvantitativno analizirati navedenu pojavu, a koji se može primijeniti i na neke važnije slučajeve praktičnih sustava uzemljenja.

Najjednostavnija geometrija pomoću koje se može analizirati utjecaj refleksije vala od granica na kojima se mijenja valna impedancija sastoji se od vertikalno ukopanog cilindričnog uzemljivača i spojnog voda konačnih dimenzija. Kako bi raščlamba bila pojednostavljena, prikladno je pretpostaviti jednaki promjer cijevi ispod tla (uzemljivača) i nadzemne geometrije (zemljovoda). Promjenom duljine spojnog voda (zemljovoda) moguće je analizirati utjecaj nadzemne geometrije na potencijal na mjestu spoja uzemljivača i zemljovoda (slika 3).

Harmonijski članovi struje groma opisane dvostruko eksponencijalnom funkcijom u izrazu (27) određeni su korištenjem brze Fourierove transformacije [8], [9]. Za uzemljivač je uzeta vertikalno ukopana cilindrična cijev, polumjera $2\ \mathrm{cm}$ Utjecaj duljine zemljovoda na dinamički odziv uzemljivača razmatran je za dvije različite duljine zemljovoda: $l_0 = 3\ \mathrm{m}$ i $30\ \mathrm{m}$. Pri duljini zemljovoda od $3\ \mathrm{cm}$ odziv će biti približno jednak odzivu kada je duljina zemljovoda zanemarena. Duljina zemljovoda od $30\ \mathrm{cm}$ približno odgovara visini stupova dalekovoda.

Kako se odziv uzemljivača uvelike razlikuje za duge i kratke uzemljivače, za kratki uzemljivač odabrana je cijev duljine $2{,}5\ \mathrm{m}$. Za dugi uzemljivač uzeta je cijev duljine $20\ \mathrm{m}$. Premda se vertikalni uzemljivači te duljine ne koriste u praksi, odabran je takav primjer kako bi u analizi bio

7 TRANSIENT RESPONSE TO IMPULSE EXCITATION

Analysis of the impulse response of a ground electrode is not sufficient. It is necessary to analyze the grounding system, consisting of ground electrodes and grounding conductors (poles) [3]. When lightning strikes a grounding system, the lightning stroke impulse encounters changes in wave impedance on its way toward the ground electrode, resulting in wave reflections [11].

Since the geometry is of finite dimensions, multiple reflections occur that must be taken into account for the correct determination of the response of the grounding system and designing (dimensioning) the protection. For the purposes of theoretical considerations, it is necessary to find the simplest possible model in order to analyze this phenomenon qualitatively and quantitatively, which can also be applied to some more important cases of practical grounding systems.

The simplest geometry that can be used to analyze the effect of the wave reflection from the boundaries at which the wave impedance changes consists of a vertical buried cylindrical ground electrode and a connecting conductor of finite dimensions. In order to simplify analysis, it is convenient to assume a uniform diameter of the pipe below the ground (ground electrode) and the overhead geometry (grounding conductor). By changing the length of the connecting conductor, it is possible to analyze the impact of the overhead geometry on the potential at the connection point of the ground electrode and the grounding conductor (Figure 3).

The harmonic current components of lightning stroke current described by the double exponential function in expression (27) are determined by using a fast Fourier transformation [8] and [9]. The ground electrode is a vertical buried cylindrical pipe with a $2\ \mathrm{cm}$ radius. The impact of the grounding conductor on the transient response of the ground electrode is considered for two different lengths of the ground electrode: $l_0 = 3\ \mathrm{m}$ and $30\ \mathrm{cm}$ When the grounding conductor is $3\ \mathrm{m}$ long, the response is approximately the same as when the electrode conductor length is ignored. The ground electrode length of $30\ \mathrm{m}$ approximately corresponds to the height of the transmission line poles.

The response of a short ground electrode is different than for a long one. A pipe of $2{,}5\ \mathrm{m}$ in length is chosen for the short ground electrode and of $20\ \mathrm{m}$ in length for the long ground electrode. Although vertiistaknut utjecaj duljine uzemljivača. Utjecaj parametara tla promatran je kroz promjenu otpornosti tla, te su odabrane dvije vrijednosti od $100\ \Omega m$ i $1\ 000\ \Omega m$. Na svakoj slici prikazane su tri krivulje potencijala na mjestu spoja uzemljivača i zemljovoda za tri različita vremena čela strujnog impulsa opisanog dvostrukom eksponencijalnom funkcijom.

Trajanje strujne pobude je $250\ \mu s$, amplituda je normirana te iznosi $1\ A$, vremena čela i začelja iznose: $t_{max} / t_{1/2} = 1/50\ \mu s/\mu s$, $t_{max} / t_{1/2} = 3/50\ \mu s/\mu s$, $t_{max} / t_{1/2} = 5/50\ \mu s/\mu s$. Za sve analizirane slučajeve pretpostavljena je relativna dielektričnost tla, te relativna permeabilnost 1.

8 NUMERIČKI REZULTATI

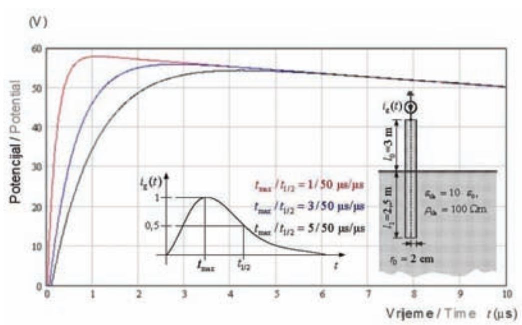
Na slici 4 prikazane su krivulje potencijala na mjestu spoja kratkog uzemljivača duljine $2{,}5\ m$ i zemljovoda duljine $3\ m$ za tri različita vremena čela strujnog vala. Otpornost tla iznosi $100\ \Omega m$.

cal ground electrodes of this length are not used in practice, such an example was chosen in order to emphasize the impact of the ground electrode length. The influence of the soil parameters was observed through change in the soil resistivity. Two values were selected, $100\ \Omega m$ and $100\ \Omega m$. In each figure, three potential curves at the connection point of the ground electrode and the grounding conductor were shown for three different time to peak current impulse values, described by a double exponential function.

The duration of the current excitation is the amplitude is $250\ \mu s$ standardized at $1\ A$ time to peak and time to half-value: $t_{max} / t_{1/2} = 1/50\ \mu s/\mu s$, $t_{max} / t_{1/2} = 3/50\ \mu s/\mu s$, $t_{max} / t_{1/2} = 5/50\ \mu s/\mu s$. For all the cases analyzed, relative soil permittivity of 10 and relative permeability of 1 are assumed.

8 NUMERICAL RESULTS

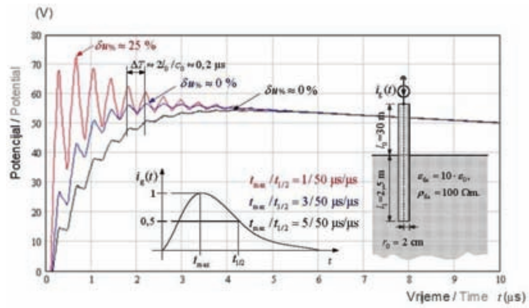
Figure 4 presents the potential curves at the connection point of the short ground electrode, $2{,}5\ m$ in length, and the grounding conductor, $3\ m$ in length, for three different time to peak current waves. The soil resistivity is $100\ \Omega m$.



Slika 4 — Potencijal na granici tlo-zrak, na mjestu spoja uzemljivača i zemljovoda
Figure 4 — Potential at the soil-air boundary, the connection point of the ground electrode and the grounding conductor.

Na slici 5 prikazane su krivulje potencijala na mjestu spoja kratkog uzemljivača duljine $2{,}5\ m$ i zemljovoda duljine $30\ m$ za tri različita vremena čela strujnog vala. Otpornost tla iznosi $100\ \Omega m$.

In Figure 5, the potential curves are presented at the connection point of the short ground electrode, $2{,}5\ m$ in length, and the grounding conductor, $30\ m$ in length, for three different time to peak current waves. The soil resistivity is $100\ \Omega m$.

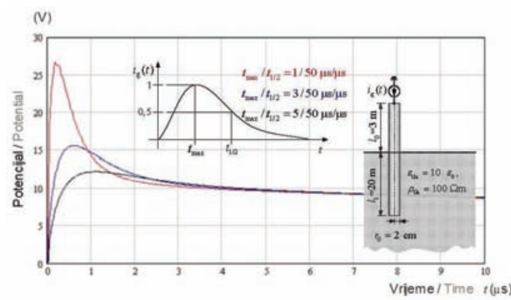


Slika 5 — Potencijal na granici tlo-zrak, na mjestu spoja uzemljivača i zemljovoda, , te postotne promjene tjemene vrijednosti potencijala u odnosu na sliku 4

Figure 5 — Potential at the soil-air boundary, the connection point of the ground electrode and the grounding conductor, and the percentage changes of the peak potential values in comparison to Figure 4.

Na slici 6 prikazane su krivulje potencijala na mjestu spoja dugog uzemljivača duljine 20 m i zemljovoda duljine 3 m za tri različita vremena čela strujnog vala. Otpornost tla iznosi 100 Ωm.

In Figure 6, the potential curves are presented at the connection point of the long ground electrode, 20 m in length, and the grounding conductor, 3 m in length, for three different time to peak current waves. The soil resistivity is 100 Ωm.

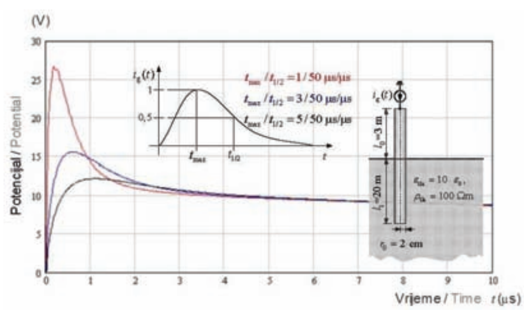


Slika 6 — Potencijal na granici tlo-zrak, na mjestu spoja uzemljivača i zemljovoda

Figure 6 — Potential at the soil-air boundary, the connection point of the ground electrode and the grounding conductor.

Na slici 7 prikazane su krivulje potencijala na mjestu spoja dugog uzemljivača duljine 20 m i zemljovoda duljine 3 m za tri različita vremena čela strujnog vala. Otpornost tla iznosi 100 Ωm.

In Figure 7, the potential curves are presented at the connection point of the long ground electrode, 20 m in length, and the grounding conductor, 3 m in length, for three different time to peak current waves. The soil resistivity is 100 Ωm.

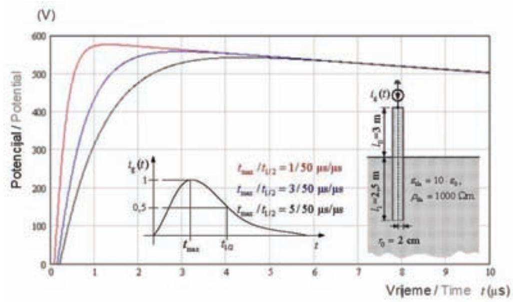


Slika 7 — Potencijal na granici tlo-zrak, na mjestu spoja uzemljivača i zemljovoda, te postotne promjene tjemene vrijednosti potencijala u odnosu na sliku 6

Figure 7 — Potential at the soil-air boundary, the connection point of the ground electrode and the grounding conductor, and the percentage changes of the peak potential values in comparison to Figure 6

Na slici 8 prikazane su krivulje potencijala na mjestu spoja kratkog uzemljivača duljine 2,5 m i zemljovoda duljine 3 m za tri različita vremena čela strujnog vala. Otpornost tla iznosi 1 000 Ωm.

In Figure 8, the potential curves are presented at the connection point of the short ground electrode, 2,5 m in length, and the grounding conductor, 3 m in length, for three different time to peak current waves. The soil resistivity is 1 000 Ωm.

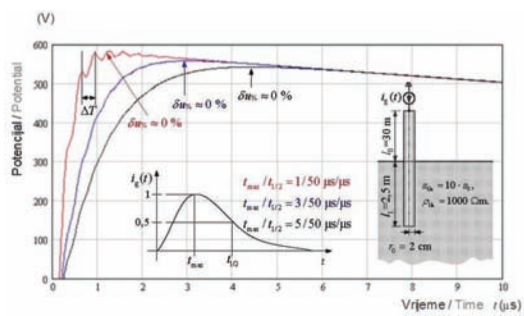


Slika 8 — Potencijal na granici tlo-zrak, na mjestu spoja uzemljivača i zemljovoda

Figure 8 — Potential at the soil-air boundary, the connection point of the ground electrode and the grounding conductor.

Na slici 9 prikazane su krivulje potencijala na mjestu spoja kratkog uzemljivača duljine 2,5 m i zemljovoda duljine 30 m za tri različita vremena čela strujnog vala. Otpornost tla iznosi 1 000 Ωm.

In Figure 9, the potential curves are presented at the connection point of the short ground electrode, 2,5 m in length, and the grounding conductor, 30 m in length, for three different time to peak current waves. The soil resistivity is 1 000 Ωm.

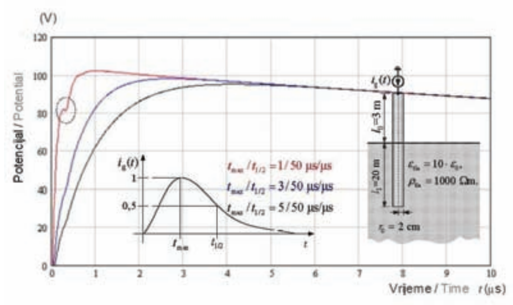


Slika 9 — Potencijal na granici tlo-zrak, na mjestu spoja uzemljivača i zemljovoda, te postotne promjene tjemene vrijednosti potencijala u odnosu na sliku 8

Figure 9 — Potential at the soil-air boundary, the connection point of the ground electrode and the grounding conductor, and the percentage changes of the peak potential values in comparison to Figure 8

Na slici 10 prikazane su krivulje potencijala na mjestu spoja dugog uzemljivača duljine 20 m i zemljovoda duljine 3 m za tri različita vremena čela strujnog vala. Otpornost tla iznosi 1 000 Ωm.

In Figure 10, the potential curves are presented at the connection point of the long ground electrode, 20 m in length, and the grounding conductor, 3 m in length, for three different time to peak current waves. The soil resistivity is 1 000 Ωm.

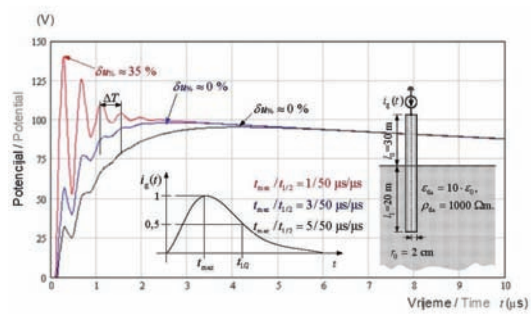


Slika 10 — Potencijal na granici tlo-zrak, na mjestu spoja uzemljivača i zemljovoda

Figure 10 — Potential at the soil-air boundary, the connection point of the ground electrode and grounding conductor

Na slici 11 prikazane su krivulje potencijala na mjestu spoja dugog uzemljivača duljine 20 m i zemljovoda duljine 30 m za tri različita vremena čela strujnog vala. Otpornost tla iznosi 1 000 Ωm.

In Figure 11, the potential curves are presented at the connection point of the long ground electrode, 20 m in length, and the grounding conductor, 30 m in length, for three different time to peak current waves. The soil resistivity is 1 000 Ωm.



Slika 11 — Potencijal na granici tlo-zrak, na mjestu spoja uzemljivača i zemljovoda, te postotne promjene tjemene vrijednosti potencijala u odnosu na sliku 10

Figure 11 — Potential at the soil-air boundary, the connection point of the ground electrode and the grounding conductor, and the percentage changes of the peak potential values in comparison to Figure 10

9 ANALIZA REZULTATA

Krivulje potencijala na svim slikama od 4 do 11 imaju zajedničko svojstvo da se ujednačuju nakon nekoliko mikrosekundi. Naime, na početni dio valnog oblika krivulja potencijala te na njihove tjemene (maksimalne) vrijednosti izraženiji utjecaj imaju visoki harmonički članovi strujne pobude, a kako vrijeme odmiče raste utjecaj nižih harmoničkih članova strujne pobude.

Relativna zastupljenost visokofrekvencijskih (VF) harmoničkih članova u spektru frekvencija valnog oblika strujne pobude pri konstantnom vremenu začelja i trajanju pobude raste sa smanjivanjem njezinog vremena čela. Iz tog razloga vrijeme čela strujne pobude utječe na početni dio krivulje potencijala, a nakon pojave maksimuma na oblik krivulje potencijala izraženiji utjecaj imaju vrijeme

9 RESULTS OF ANALYSIS

The potential curves in Figures 4 to 11 acquire the same value after several microseconds. The high harmonic components of the current excitation have a greater effect on the wave front and the peak value (maximum) of the potential curve and with time the effect of the lower harmonic components of the current excitation increases.

The relative percentage of high frequency (HF) harmonic components in the frequency spectrum of the current excitation wave shape when the time to half-value and excitation time are constant increases as the time to peak value decreases. For this reason, the time to peak value of the current excitation affects the wave front of the potential curve, and after the peak value the time to half-value and the duration of the current excitation začelja i trajanje strujne pobude. Kako su vrijeme začelja i trajanje strujne pobude na svakoj prikazanoj slici konstantne veličine, oblici funkcija potencijala se nakon pojave maksimuma ujednačuju, odnosno teže k istoj vrijednosti.

S obzirom da smanjenje vremena čela strujne pobude pri njezinom konstantnom vremenu začelja i trajanju uzrokuje povećanje udjela VF komponenti u spektru frekvencija valnog oblika pobude, povećavat će se i utjecaj VF komponenti na odziv. Pojave koje dolaze do izražaja pri visokim frekvencijama su refleksije valova i smanjenje aktivne duljine uzemljivača. Na slici 4 vidljiv je utjecaj smanjenja vremena čela strujne pobude na povećanje maksimalne vrijednosti napona. Uzrok povećanju maksimalne vrijednosti potencijala na slici 4 vezan je za smanjenje aktivne duljine uzemljivača. Naime, smanjenjem vremena čela strujne pobude povećan je udio VF članova u spektru frekvencija strujne pobude, što dovodi do smanjenja duljine uzemljivača kojom on aktivno odvodi struju u okolno tlo. Stoga se povećava otpor rasprostiranja uzemljivača, a time i maksimalna vrijednost potencijala.

Smanjenje aktivne duljine uzemljivača izraženije je kod duljih uzemljivača, što se može potvrditi usporedbom slike 4, koja se odnosi na kratki uzemljivač, sa slikom 6, koja se odnosi na dugi uzemljivač. Prema slici 4 smanjenje vremena čela strujne pobude s 5 μs na 1 μs povećalo je maksimalni iznos potencijala s 55 V na 57 V, što je približno 3,5 %, dok se prema slici 6 potencijal povećao s 12,5 V na 27 V, što je približno 115 %.

Usporedbom krivulja potencijala na slikama 8 i 10 s onima na slikama 4 i 6, dobiva se uvid kako se odražava promjena otpornosti tla na smanjenje aktivne duljine kratkog i dugog uzemljivača. Prema slici 8, koja se odnosi na kratki uzemljivač u loše vodljivom tlu, smanjenje vremena čela s 5 μs na 1 μs povećalo je maksimalni iznos potencijala s 550 V na 570 V, što je približno 3,5 %, dok se prema slici 10, koja se odnosi na dugi uzemljivač u loše vodljivom tlu, potencijal povećao s 95 V na 102 V, što je približno 8 %. Prethodno opisana promjena maksimalne vrijednosti potencijala na slici 4, koja se odnosi na kratki uzemljivač u dobro vodljivom tlu iznosi 3,5 %, a na slici 6, koja se odnosi na dugi uzemljivač u dobro vodljivom tlu, približno 115%. Dakle, povećanje otpornosti tla **smanjuje utjecaj strmine na** maksimum potencijala, što je posebno izraženo kod dugih uzemljivača, jer je kod njih jako izraženo smanjenje aktivne duljine, ali se istodobno **pogoršava statički odziv,** tj. iznosi potencijala su veći.

Povećanjem otpornosti tla povećava se djelatni otpor odvoda (slika 2) u svim analiziranim slu-

have a greater effect on the shape of the potential curve. Since the time to half-value and the duration of the current excitation are constant values in all the figures, the shapes of the potential curves become identical after the peak, i.e. they tend toward the same value.

Decreasing the time to peak value of current excitation when its time to half-value and duration are constant causes an increase in the share of high frequency components in the frequency spectrum of the current excitation wave shape. The influence of HF components on the response will also increase. The phenomena that occur at high frequencies are wave reflections and the reduction of the active length of the ground electrode. In Figure 4, the influence of the decreased time to peak value of the current excitation on the increase of the maximum voltage values is evident. The cause of the increased maximum potential in Figure 4 is due to the decrease of the active length of the ground electrode. By decreasing the time to peak of the current excitation, the share of HF components in the frequency spectrum of current excitation is increased, which leads to a decrease in the length of the ground electrode which actively conducts the current into the surrounding soil. Therefore, the propagation resistance of the ground electrode is increased and, thereby, the maximum potential value.

Decreasing the active length of the ground electrode is more marked in longer ground electrodes, as can be confirmed by comparing Figure 4, which refers to a short ground electrode, to Figure 6, which refers to a long ground electrode. According to Figure 4, decreasing the time to peak value of the current excitation from 5 μs to 1 μs increased the maximum potential from 55 V to 57 V, which is approximately 3,5 % while according to Figure 6 the potential increased from 12,5 V to 27 V, which is approximately 115 %.

By comparing the potential curves in Figures 8 and 10 with those in Figures 4 and 6, insight is obtained into how changes in the soil resistivity affect the decrease in the active lengths of short and long ground electrodes. According to Figure 8, which refers to a short ground electrode in poorly conducting soil, decreasing the time to peak value from 5 μs to 1 μs increased the maximum potential value from 550 V to 570 V, which is approximately 3,5 %, while according to Figure 10, which refers to a long ground electrode in poorly conducting soil, the potential increased from 95 V to 102 V, which is approximately 8%. The previously described change in the maximum potential value in Figure 4, which refers to a short ground electrode in well conducting soil is 3,5 %, and in Figure 6, which refers to a long ground electrode in well conducting soil, approximately 115%. Therefore, increasing the soil resistivity **reduces the rise-time impact on the maximum potential,** which is parčajevima, a time se smanjuje relativni utjecaj uzdužne impedancije pri porastu frekvencije, odnosno utjecaj viših harmoničkih članova strujne pobude na odziv. To znači da se u loše vodljivom tlu može očekivati manja izraženost tjemene vrijednosti potencijala u odnosu na ostatak krivulje potencijala, te manja osjetljivost odziva na kraća vremena čela strujnih pobuda. Krivulje potencijala prikazane na slikama od 8 do 11 to i potvrđuju. Prema slici 9 nije došlo do porasta tjemene vrijednosti potencijala u odnosu na sliku 8, jedino se zapaža promjena valnog oblika krivulje potencijala za pobudu oblika $t_{max} / t_{1/2} = 1/50$ μs/μs, koji je postao valovit u odnosu na sliku 8.

Usporedbom parova slika 4 i 5, 6 i 7, 8 i 9, te 10 i 11, dobiva se uvid o utjecaju geometrije iznad tla na iznos i oblik krivulja potencijala koji se javlja na mjestu spoja uzemljivača i nadzemne geometrije. Usporedbom krivulja potencijala na slikama 4 i 5, zapaža se da krivulje potencijala na slici 5 za razliku od slike 4 karakterizira **valovitost** valnog oblika. Valovitost je posljedica višestrukih refleksija strujnog vala između točke utiskivanja struje u zemljovod i mjesta na kojemu su spojeni uzemljivač i zemljovod. Vrijeme između dvije uzastopne refleksije na slici 5 označeno je s ΔT i iznosi približno 0,2 μs. Smanjenjem vremena čela struje pobude utjecaj zemljovoda se povećava: tako je na primjer na slici 5 maksimum potencijala na krivulji koja se odnosi na vrijeme čela strujnog vala od 1 μs povećan u odnosu na sliku 4 za oko 25 %. Pri većim vremenima čela strujnog vala ova promjena se ne opaža. Za očekivati je da će utjecaj povećanja duljine zemljovoda na odziv biti izraženiji kod dugog uzemljivača, što i potvrđuje usporedba istovjetnih krivulja potencijala na slikama 6 i 7. Naime, prema slici 7, osim promjene oblika krivulja potencijala zbog povećanja duljine zemljovoda, koji je postao valovit, potencijal na mjestu spoja zemljovoda i uzemljivača povećao se za sve promatrane valne oblike strujne pobude.

Povećanje maksimalne vrijednosti potencijala najizraženije je za najstrmiju strujnu pobudu, te iznosi oko 90 %. Pri strujnim pobudama oblika $t_{max} / t_{1/2} = 3/50$ μs/μs, $t_{max} / t_{1/2} = 5/50$ μs/μs povećanje potencijala na slici 7 u odnosu na sliku 6 iznosi 40 %, odnosno 20 %. Za razliku od kratkog uzemljivača, kod dugog uzemljivača promjene iznosa maksimalne vrijednosti potencijala nastupaju pri blažim nagibima čela strujnih pobuda, te je ujedno promjena po iznosu veća. Zbog izraženijeg smanjenja aktivne duljine uzemljivača u odnosu na kratki uzemljivač utjecaj povećanja potencijala zbog povećanja duljine zemljovoda javlja se i pri blažim nagibima strujne pobude. Kako povećanje otpornosti tla ublažava pojavu smanjenja aktivne duljine

ticularly evident for long ground electrodes, because their active length is markedly decreased, while at the same time the **static response worsens,** i.e. the potential values are higher.

By increasing the soil resistivity, the active resistance of the conductance is increased (Figure 2) in all the cases analyzed, and thereby the relative influence of the longitudinal impedance is decreased when frequency increases, i.e. the influence of higher harmonic components of the current excitation on the response. This means that in poorly conductive soil, the impact of the peak potential values can be expected to be lower in comparison to the rest of the potential curve, and lower sensitivity of the response to the shorter time to peak of the current excitation. The potential curves presented in Figures 8 to 11 confirm this. According to Figure 9, there was no increase in the peak values of the potential in comparison to Figure 8. The only change noted was in the wave shape of the potential curves for the excitation shape $t_{max} / t_{1/2} = 1/50$ μs/μs, which became wavy in comparison to Figure 8.

By comparing the figure pairs 4 and 5, 6 and 7, 8 and 9, and 10 and 11, insight is obtained into the influence of the overhead geometry on the value and shape of the potential curves that occur at the connection point of the ground electrode and overhead geometry. By comparing the potential curves in Figures 4 and 5, it is noted that the potential curve in Figure 5, unlike that in Figure 4, is characterized by **waviness** of the wave shape. This waviness is a consequence of multiple reflections of the current wave between the current injection point in the ground electrode and the connection point of the ground electrode and the grounding conductor. The time between two consecutive reflections in Figure 5 is indicated by ΔT and is approximately 0,2 μs. By reducing the time to peak value of the current excitation, the influence of the grounding conductor is increased. Thus, for example, in Figure 5 the maximum potential on the curve that designates the time to peak value of the current wave of 1 μs is increased in comparison to Figure 4 by approximately 25 %. With a longer time to peak value of the current wave, this change is not noted. It could be expected that the impact of increasing the length of the grounding conductor on the response would be more marked for a long ground electrode, which is confirmed by comparing the identical potential curves in Figures 6 and 7. According to Figure 7, in addition to the changes in the shape of the potential curves due to the increased length of the grounding conductor, which became wavy, the potential at the connection point of the grounding conductor and the ground electrode increased for all the observed wave shapes of the excitation current.

The increased maximum potential values are most marked for the steepest current excitation, and are uzemljivača, pri povećanju otpornosti tla smanjit će se i utjecaj duljine zemljovoda na odziv uzemljivača, pogotovo kod dugih uzemljivača. Iz tog razloga su promjene iznosa tjemenih vrijednosti potencijala na slici 11 u odnosu na sliku 10 manje nego li što je to slučaj sa slike 7 u odnosu na sliku 6.

Jedino je na slici 10 uočljiva pojava refleksije strujnog vala od slobodnog kraja uzemljivača. Pojava refleksije od slobodnog kraja uzemljivača vidljiva je na krivulji potencijala koja odgovara strujnoj pobudi oblika $t_{max} / t_{1/2}$ = 1/50 μs/μs kao propad potencijala, a koji se javlja nakon 0,4 μs od početka prijelazne pojave. Kako je uzemljivač duljine 20 m, vrijeme potrebno da strujni val prevali put do njegovog slobodnog kraja i natrag na početak pri relativnoj dielektričnosti tla 10, iznosi približno 0,4 μs.

10 ZAKLJUČAK

Na temelju prikazanih odziva sustava uzemljenja, kojeg tvore uzemljivač i zemljovod, iskazanog potencijalom na mjestu spoja uzemljivača i zemljovoda i samoga uzemljivača može se zaključiti da se prilikom određivanja dinamičkog odziva sustava uzemljenja **mora uzeti u razmatranje i geometrija vodiča iznad tla, a ne samo uzemljivač.**

Udaljavanjem točke utiskivanja struje od spoja vodiča uzemljivača i vodiča iznad tla, ovojnica odziva vremenske promjene potencijala poprima oblik napona koji se javlja u slučaju da je vodič iznad tla beskonačno dug. U tom slučaju potencijal teorijski može poprimiti najviše **dvostruku vrijednost potencijala** koji bi se javio zbog direktnog utiskivanja struje u uzemljivač. Dinamički odziv sustava uzemljenja ovisi o strmini vala, tj. udjelu VF komponenti u valnom obliku, udaljenosti točke utiskivanja od spoja dvaju različitih impedancija i od otpornosti tla. Utjecaj refleksije vala od slobodnog kraja uzemljivača u tlu na naponske prilike se može zanemariti u odnosu na utjecaj refleksije vala od slobodnog kraja vodiča iznad tla.

Iako to u ovom radu nije prikazano kada je tlo male otpornosti (ispod 100 Ωm), tada je utjecaj nadzemne geometrije jako izražen, pogotovo kod dugih uzemljivača. **Iako krivulje potencijala ukazuju da povećanje otpornosti tla ima blagodatan utjecaj na dinamički odziv, treba imati na umu da se na taj način statički odziv pogoršava**. Ujedno, poznato je da se povećanjem duljine vertikalnog štapnog uzemljivača smanjuje utjecaj granice tlo-zrak na uzemljivač jer se povećava geometrijska udaljenost točaka na uzemljivaču od granice.

approximately 90 %. For current excitation shapes $t_{max} / t_{1/2}$ = 3/50 μs/μs, $t_{max} / t_{1/2}$ = 5/50 μs/μs, the increased potential in Figure 7 in comparison to Figure 6 is 40 % or, respectively, 20 %. Unlike a short ground electrode, for a long ground electrode the changes in the maximum potential values occur at slower rise-times of the current excitations and the change in the amount is greater. Due to the markedly decreased active length of the long ground electrode in comparison to the short ground electrode, the influence of the increased potential due to the increased length of the grounding conductor also occurs at slower rise-times of the current excitation. Since increasing soil resistivity diminishes the phenomenon of decreasing the active length of the ground electrode, increasing soil resistivity will decrease the influence of the length of the grounding conductor on the response of the ground electrode, especially long ground electrodes. For this reason, the changes in the peak potential values in Figure 11 in comparison to Figure 10 are less than in the case of Figure 7 in comparison to Figure 6.

The reflection of the current wave from the free end of the ground electrode is only evident in Figure 10. Reflection from the free end of the ground electrode is evident on the potential curve that corresponds to the current excitation shape $t_{max} / t_{1/2}$ = 1/50 μs/μs as a drop in potential, which occurs after 0,4 μs from the beginning of the transient phenomenon. Since the ground electrode is 20 m in length, the time required for the current wave to travel to its free end and back to the beginning at a relative soil permittivity of 10 is approximately 0,4 μs.

10 CONCLUSION

On the basis of the responses by the grounding system presented, consisting of a ground electrode and grounding conductor, expressed by the potential at the connection point of the ground electrode and grounding conductor, and the ground electrode itself, it can be concluded that when determining the transient response of the grounding system, **it is necessary to take the geometry of the overhead conductor into account, and not only that of the ground electrode.**

By increasing the distance between the current injection point at the connection point of the ground electrode and overhead conductor, the envelope of the time varying potential response assumes the voltage shape that occurs in the event that the overhead conductor is infinitely long. In this case, the potential can theoretically acquire a maximum of **double the potential value** that would occur due to direct current injection into the ground electrode. The transient response of the grounding system depends on the steepness of the wave, i.e. the percentage of HF components in the wave shape, the

Na taj način otpor rasprostiranja pri statičkom odzivu je manji nego li što bi bio samo zbog povećanja duljine vodiča. Međutim, kod dinamičkog odziva ovu pojavu nadjačava smanjenje aktivne duljine vodiča, što potvrđuju prikazani rezultati.

Iz tog razloga pri dimenzioniranju uzemljivača za zaštitu od groma preporučljivo je koristiti više kraćih, međusobno razmaknutih vertikalnih cijevi.

distance of the injection point from the connection point of two different impedances and soil resistivity. The influence of the wave reflection from the free end of the ground electrode in the soil on the voltage conditions can be ignored in comparison to the influence of the wave reflection from the free end of the overhead conductor.

Although not described in this paper, when the soil resistivity is low (below $100\ \Omega m$), the influence of the overhead geometry is considerable, especially for long ground electrodes. **Although potential curves indicate that increased soil resistivity has a beneficial influence on the transient response, it is necessary to bear in mind that the static response worsens.** At the same time, it is known that increasing the length of the vertical ground rod electrode decreases the influence of the soil-air boundary on the ground electrode because the geometrical distance is increased between the points on the electrode and the boundary.

In this manner, the propagation resistance during the static response is lower than it would be by merely increasing the length of the conductor. However, the active length of the conductor has a greater influence than this phenomenon, as confirmed by the results presented.

For these reasons, when designing (dimensioning) ground electrodes for lightning protection, the use of several short, appropriately spaced vertical pipe electrodes is recommended.

LITERATURA / REFERENCES

[1] PADELIN, M., Zaštita od groma, Školska knjiga, Zagreb, 1987.
[2] SERAUDIE, CH., LV surges and surge arresters, Cahier Technique No. 179, Schneider Electric, March 1999
[3] MAJDANDŽIĆ, F., Uzemljivači i sustavi uzemljenja, Graphis, Zagreb, 2004.
[4] ŽUTOBRADIĆ, S., Doprinos istraživanju impulsnih karakteristika uzemljivača, doktorska disertacija, Zagreb, 1989.
[5] GRCEV, L, DAWALIBI, F., An Electromagnetic Model for Transients in Gounding Systems, IEEE Trans. Power Delivery, Vol. 5, No. 4. 1990
[6] CIU, B. Z., ZHAO, Z., YIN, H., COMPEL, L.L., An electromagnetic approach to analyze the performance of the substation's grounding grid in high frequency domain, The International Journal for Computation and Mathematics in Electrical and Electronic Engineering, Vol. 22, No. 3, 2003
[7] LIU, Y., Transient Response of Grounding Systems Caused by Lightning: Modelling and Experiments, Dissertation presented at Uppsala University to be publicly examined in Haggsalen, Angstromlaboratoriet, Uppsala, 2004
[8] HARRIS, J. W., HORST STOCKER, Handbook of Mathematics and Computational Science, Springer – Verlag New York, Inc., 1988
[9] SPIEGEL, M. R., Fourier Analysis with Applications to Boundary Value Problems, Schoum's Outline Series, McGraw-Hill, USA, 1974
[10] GRCEV, L., POPOV, M.,On High-Frequency Circuit Equivalents of a Vertical Ground Rod, IEEE Transactions on Power Delivery, Vol. 20, No. 2, April 2005
[11] HAZNADAR, Z., ŠTIH, Ž., Elektromagnetizam, Školska knjiga, Zagreb, 1997.
[12] MACHAČ, J.,Theory Of Electromagnetic Field, Fakulta Elektrotechnika, Češke vysoke učeni technicke v praze, Prague, 2002
[13] MEDIĆ, M., Modeliranje uzemljivača s utjecajem izmjeničnog magnetskog polja, Doktorska disertacija, Split, 1999.
[14] ŽUTOBRADIĆ, S., HAZNADAR, Z., GAČANOVIĆ, R., KOROMAN, V., Impulsne značajke uzemljivača elektroenergetskih postrojenja, Elektrotehnika, br. 1-2, Logotip, Zagreb, siječanj – travanj 1999.

Adrese autora:

Dr. sc. **Tomislav Barić**
tbaric@inet.hr
Sveučilište J.J. Strossmayer
Elektrotehnički fakultet Osijek
Kneza Trpimira 2b
31000 Osijek
Hrvatska
Prof. dr. sc. **Zijad Haznadar**
zijad.haznadar@fer.hr
Prof. dr. sc. **Sead Berberović**
sead.berberovic@fer.hr
Sveučilište u Zagrebu
Fakultet elektrotehnike i računarstva
Unska 3
10000 Zagreb
Hrvatska

Authors' Adresses:

Tomislav Barić, PhD
tbaric@inet.hr
University of J.J. Strossmayer, Faculty of Electrical Engineering
Kneza Trpimira 2b
31000 Osijek
Croatia
Prof. **Zijad Haznadar**, PhD
zijad.haznadar@fer.hr
Prof. **Sead Berberović**, PhD
sead.berberovic@fer.hr
University of Zagreb
Faculty of Electrical Engineering and Computing
Unska 3
10000 Zagreb
Croatia

Uredništvo primilo rukopis:
2007-12-07

Prihvaćeno:
2008-01-18

Manuscript received:
2007-12-07

Accepted:
2008-01-18