KAPACITIVNI UTJECAJ VISOKONAPONSKIH NADZEMNIH VODOVA NA MJERENJE SPECIFIČNOG OTPORA TLA

CAPACITIVE INFLUENCE OF HIGH VOLTAGE OVERHEAD TRANSMISSION LINES ON THE MEASUREMENT OF SOIL RESISTIVITY

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U radu je prikazana analiza utjecaja visokonaponskih nadzemnih vodova na mjerenja specifičnog otpora tla. Analizom je određena razina smetnji pri mjerenju zbog blizine faznih vodiča visokonaponskog nadzemnog voda. Tlo je modelirano kao anizotropni homogeni poluprostor konačne otpornosti. Kako bi članak bio od koristi inženjerima u praksi, korišten je jednostavni matematički instrumentarij, s detaljno prikazanim izvodima i fizikalno objektivnim pretpostavkama pod kojima je navedeni model valjan. Radi jednostavnosti i općenitosti izlaganja analiza je provedena na praktičnom primjeru mjerenja specifičnog otpora tla Wennerovom metodom. Primjer se odnosi na jednosistemski visokonaponski dalekovod s čelično rešetkastim stupom tzv. jela. Rezultati dobiveni prikazanom teorijom uspoređeni su s rezultatima dobivenim profesionalnim programskim paketom CDEGS. Rezultati su prikazani analitički i grafički te diskutirani.

In this article, an analysis is presented of the impact of high voltage overhead transmission lines on the measurement of soil resistivity. Through analysis, the measurement noise level due to the vicinity of the phase conductors of a high voltage overhead transmission line is determined. The soil is modeled as an anisotropic homogeneous half-space of finite resistivity. In order for the article to be of practical use to engineers, simple mathematical instrumentation has been used. Detailed expressions and the physically objective hypotheses under which the cited model is valid have been derived. For the simplicity and generality of the presentation, analysis was performed using a practical example of the measurement of soil resistivity by the Wenner method. The example refers to a single system high voltage transmission line with a steel tower. The results obtained by the theory presented are compared to the results obtained with the software package CDEGS (Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis). The results obtained are presented analytically, graphically and are discussed.

Ključne riječi: elektromagnetski šum, specifični otpor tla, Wennerova metoda
Key words: electromagnetic noise, soil resistivity, Wenner method

Barić, T., Glavaš, H., Jozsa, L., Kapacitivni utjecaj visokonaponskih nadzemnih vodova..., Energija, god. 56(2007), br. 2., str. 232–249
Barić, T., Glavaš, H., Jozsa, L., Capacitive Influence of High Voltage Overhead Transmission..., Energija, vol. 56(2007), No. 2, p.p. 232–249
https://doi.org/10.37798/2007562354

1 UVOD

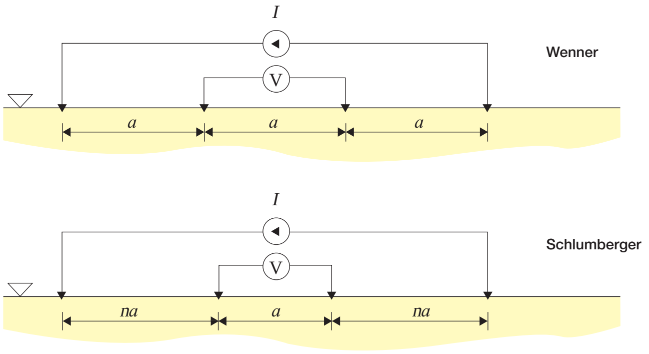
Za razliku od laboratorijskih mjerenja, mjerenja izvan laboratorija otežana su utjecajem: okoline, temperaturnim promjenama, blizinom objekata, te električnim smetnjama objekata i uređaja pod naponom. Naročito nepovoljne prilike pri mjerenju javljaju se zbog blizine objekata pod naponom, kao što su visokonaponski (VN) nadzemni vodovi, odnosno dalekovodi. Tada su mjerenja pod utjecajem nepoželjnog elektromagnetskog polja, čiji se utjecaj na mjerne rezultate teško analizira. Za takve prilike normama su dane preporuke za izvođenje mjera potrebnih za smanjenje utjecaja objekata pod naponom na mjerenje. Međutim, ukoliko navedene mjere nije moguće provesti, tada ostaje otvoreno pitanje koliku pogrešku sadrži mjerni rezultat. Jedno takvo mjerenje je mjerenje specifičnog otpora tla, kada se obavlja u blizini VN nadzemnog voda pod naponom.

Stalnim povećanjem životnog standarda i BDP zemalja Europske unije imalo je za posljedicu povećanje izgradnje proizvodnih, poslovnih i stambenih objekata unutar urbanih sredina. Povećanje cijena nekretnina u urbanim sredinama uvjetovalo je povećanje izgradnje na periferijama gradova. Na tim mjestima prijenos, odnosno distribucija električne energije obavlja se VN nadzemnim vodovima. Prilikom izgradnje novih proizvodnih, poslovnih i stambenih objekata potrebno je izvršiti mjerenje specifičnog otpora tla na građevinskoj lokaciji na kojoj će se navedeni objekti graditi. Kako se mjerenje specifičnog otpora tla obavlja na lokacijama kroz koje prolazi ili se u neposrednoj blizini nalaze VN nadzemni vodovi, čiji se utjecaj na mjerenje ne može ukloniti, postavlja se pitanje o razini utjecaja VN nadzemnih vodova na mjerenje specifičnog otpora tla. Mjerenje specifičnog otpora tla najčešće se obavlja Wennerovom [1] ili Schlumbergerovom mjernom tehnikom, odnosno rasporedom elektroda (slika 1).

1 INTRODUCTION

Unlike laboratory measurements, measurements outside laboratories are hindered by the influence of the environment, temperature changes, the vicinity of objects and electrical interference from objects and energized devices. Particularly unfavorable conditions for measurement occur due to the vicinity of energized objects, such as high voltage overhead transmission lines or power lines. In such cases, measurement is affected by an undesirable electromagnetic field, which exerts an influence on the measured results that is difficult to analyze. For such cases, standards provide recommendations and necessary procedures for reducing the influence of energized objects on measurement. However, if such measures cannot be performed, the question remains regarding the extent of the measurement error in the measured result. One such measurement is the measurement of soil resistivity, when measurement is performed in the vicinity of an energized high voltage overhead transmission line.

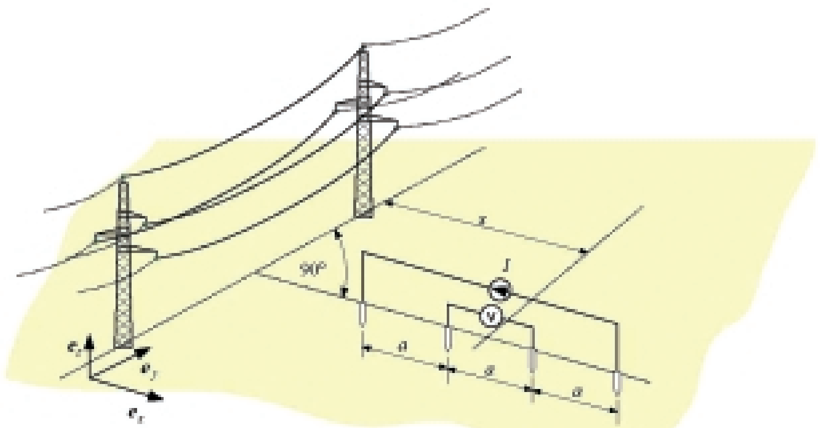
The constantly rising standard of living and GDP of the countries of the European Union resulted in the increased construction of manufacturing, office and residential buildings within urban milieus. Rising prices of real estate in urban milieus resulted in an increase in construction in the outskirts of cities. In such places, the transmission or distribution of electricity occurs via high voltage overhead transmission lines. When constructing new manufacturing, office and residential buildings, it is necessary to measure the soil resistivity of the construction site upon which the objects will be built. Since the measurement of soil resistivity is performed on locations through which high voltage overhead transmission lines either pass or are in the immediate vicinity, the influence of which upon measurement cannot be eliminated, the question is posed regarding the level of the impact of high voltage overhead transmission lines on the measurement of soil resistivity. Measurements of soil resistivity are most frequently performed using the Wenner method [1] or Schlumberger method, i.e. with electrode arrangement (Figure 1).



Slika 1
Različite konfiguracije elektroda za ispitivanje specifične otpornosti tla
Figure 1
Different electrode arrangements for measuring soil resistivity

Mjerenjenje specifičnog otpora tla Wennerovom mjernom tehnikom u blizini VN nadzemnih vodova prikazano je na slici 1. Prema preporukama [2] za mjerenje u blizini VN nadzemnih vodova pravac duž kojeg su razmještene mjerne elektrode trebao bi biti okomit na pravac duž kojeg su postavljeni dalekovodni stupovi, odnosno relativni položaj mjernog spoja u odnosu na trasu dalekovoda treba biti kao što je to prikazano na slici 2.

Measurement of soil resistivity using the Wenner method in the vicinity of high voltage overhead transmission lines is presented in Figure 1. According to recommendations [2] for measurement in the vicinity of high voltage overhead transmission lines, the line along which measuring electrodes are spaced should be perpendicular to the route along which transmission towers are placed, i.e. the relative position of the measuring points in relation to the route of the transmission lines should be as presented in Figure 2.



Slika 2
Položaj mjernih elektroda i ožičenja u odnosu na trasu VN nadzemnog voda i relevantne veličine
Figure 2
Position of measurement electrodes and wiring in relation to the route of a high voltage overhead transmission line and relevant values

U tom slučaju u velikoj mjeri se smanjuje induktivni utjecaj struja koje protječu faznim vodičima na mjerenje [3]. Međutim, iako se ovom mjerom uspješno slabi induktivna veza između faznih vodiča i ožičenja mjerenja i dalje je prisutan kapacitivni utjecaj. Kapacitivni utjecaj na mjerenje prisutan je na pogonskoj frekvenciji mreže (50 Hz), te se prikladnim izborom frekvencije rada mjernog uređaja koja je različita od mrežne (ne smije biti cjelobrojni višekratnik mrežne frekvencije zbog mogućih harmonika), postiže razdvajanje

In this case, the inductive effect of current flow in phase conductors is greatly reduced in the measurement [3]. However, although this measure successfully reduces inductive coupling between phase conductors and measurement wiring, the capacitive influence is still present. Capacitive influence on measurement is present at the network frequency (50 Hz). With the suitable choice of the operating frequency of the measuring device that is different from the network frequency (it must not be a multiple integer of the network frequency mjernog signala od smetnje frekvencije 50 Hz uz pomoć prikladnog filtra. Iz tog razloga potrebno je poznavati iznos šuma u mjerenju u odnosu na korisni signal, kao bi se odredila potrebna selektivnost filtra,odnosno utvrdila osjetljivost i selektivnost, tj. imunost na smetnje komercijalnih mjernih uređaja za navedenu namjenu [3].

due to eventual harmonics), the separation of the measuring signal from the noise frequency of 50 Hz is achieved with the aid of a suitable filter. For this reason, it is necessary to know the noise to signal ratio in the measurement in order to determine the necessary selectivity of the filter, i.e. to determine sensitivity and selectivity, i.e. the noise immunity of commercial measuring devices for this purpose [3].

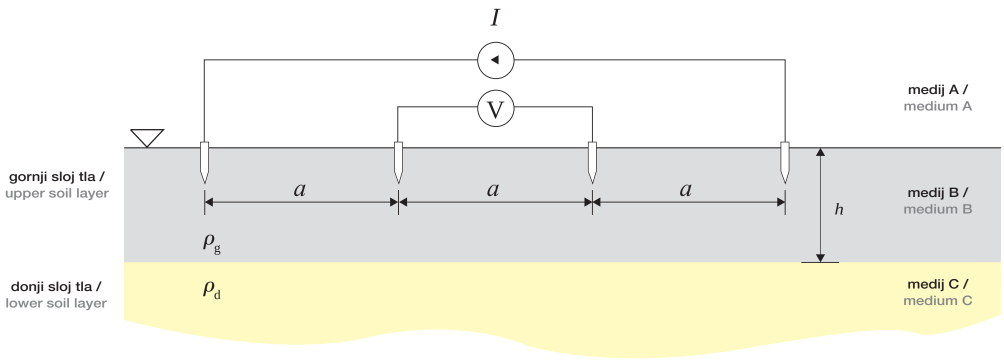
2 DVOSLOJNI MODEL TLA I WENNEROV RASPORED ELEKTRODA

Za većinu praktičnih primjena dvoslojni model tla s vertikalnom promjenom specifičnog električnog otpora se pokazao dostatnim [2]. Navedeni model tla podrazumijeva dva sloja tla: gornji i donji, koji se razlikuju u iznosu specifičnog električnog otpora. Pri tome je gornji sloj tla konačne debljine h, a donji se proteže u beskonačnost. Na osnovi navedenog takav model tla opisan je s tri značajke: specifičnim otporom gornjeg sloja ρ_g, njegovom debljinom h, te specifičnim otporom donjeg sloja ρ_d. Mjerenje specifičnog otpora tla Wennerovim rasporedom mjernih elektroda i model dvoslojnog tla s relevantnim veličinama, prikazani su na slici 3.

2 TWO-LAYER SOIL MODEL AND WENNER ELECTRODE ARRANGEMENT

For the majority of practical applications, a two-layer soil model with a vertical change in the soil resistivity has proved to be sufficient [2]. This soil model is understood to mean two layers of soil, upper and lower, which differ in the amounts of resistivity. Accordingly, the upper layer of soil is of finite thickness, h, and the lower layer extends to infinity. On the basis of the above, such a soil model is described by three characteristics: the resistivity of the upper layer, ρ_g, its thickness, h, and the resistivity of the lower layer, ρ_d. Measurement of soil resistivity with the Wenner electrode arrangement and a two-layer soil model with the relevant values is presented in Figure 3.

Slika 3
Dvoslojno tlo i Wennerov raspored elektroda
Figure 3
Two-layer soil model and the Wenner electrode arrangement



Utiskivanjem struje I kroz strujne elektrode u tlo, nastalo strujno polje u dvoslojnom tlu mora zadovoljiti rubne uvjete na granicama diskontinuiteta specifičnog električnog otpora: tlo – zrak, te gornjeg i donjeg sloj tla, a koji glase [4] i [5]:

The current field resulting from the injection of current I through the current electrodes in the two-layer soil must satisfy the boundary conditions at the discontinuity boundaries of resistivity: soil – air, and the upper and lower soil layers, as stated in [4] and [5]:

$$\boldsymbol{n}\times\left(\rho_A\boldsymbol{J}_A-\rho_B\boldsymbol{J}_B\right)=0,\quad \boldsymbol{n}\times\left(\rho_B\boldsymbol{J}_B-\rho_C\boldsymbol{J}_C\right)=0, \tag{1}$$

$$\boldsymbol{n}\cdot\left(\boldsymbol{J}_{\mathrm{A}}-\boldsymbol{J}_{\mathrm{B}}\right)=0,\quad \boldsymbol{n}\cdot\left(\boldsymbol{J}_{\mathrm{b}}-\boldsymbol{J}_{\mathrm{C}}\right)=0, \qquad (2)$$

gdje je:

$\boldsymbol{n}$ – vektor normale na granice diskontinuiteta specifičnog električnog otpora,

$\boldsymbol{J}_{\mathrm{A}}$ – gustoća struje u mediju A (zrak) na granici diskontinuiteta specifičnog električnog otpora,

$\boldsymbol{J}_{\mathrm{B}}$ – gustoća struje u mediju B (gornji sloj tla) na granici diskontinuiteta specifičnog električnog otpora i

$\boldsymbol{J}_{\mathrm{C}}$ – gustoća struje u mediju C (donji sloj tla) na granici diskontinuiteta specifičnog električnog otpora.

Zrak (medij A) ima visok specifični električni otpor, i smatra se da iznosi 10^{18} Ω·m. Poznavanje rubnih uvjeta (1) i (2) na granicama diskontinuiteta specifičnog električnog otpora omogućava matematičko rješavanje zadaće i određivanje potencijala na naponskim mjernim elektrodama (slika 4). Navedena zadaća se najčešće rješava tehnikom odslikavanja izvora polja od granica diskontinuiteta specifičnog električnog otpora. Korištenjem tehnike odslikavanja izvora polja, tj. strujnih elektroda od granice tlo–zrak i granice između gornjeg i donjeg sloja tla, uz istodobno nadomještanje štapnih elektroda s prikladnim kuglastim, zadovoljavaju se jednadžbe rubnih uvjeta: (1) i (2), a čiji je postupak pobliže opisan u [4] i [5]. Prvo odslikavanje odvija se na granici tlo–zrak, na kojoj se polukugla s kojom se nadomješta štapna elektroda odslikava u polukuglu u mediju A, kao što je to prikazano slikom 4. Slijedi odslikavanje dobivenih kugli A i D od granice gornjeg i donjeg sloja tla. Zatim se dobivena slika iz donjeg sloja tla odslikava od granice tlo–zrak, nakon čega se postupak ponavlja. Više o primjeni tehnike odslikavanja u višeslojnom tlu može se naći u [6], a o interpretaciji dobivenih veličina i mjernih podataka u [7] i [8].

where:

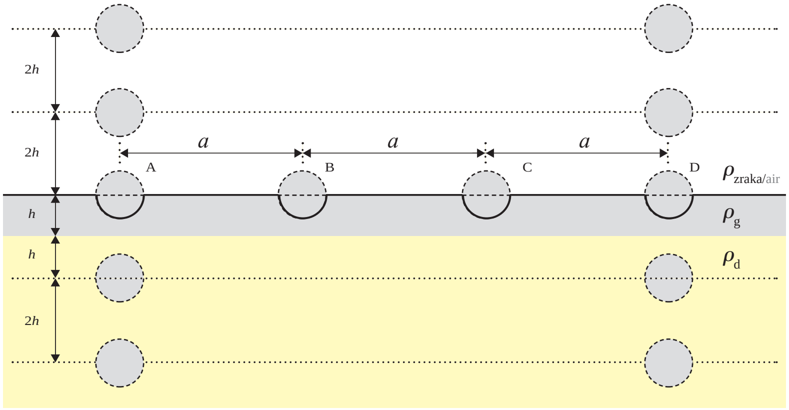
$\boldsymbol{n}$ – the normal vector at the discontinuity boundary of resistivity,

$\boldsymbol{J}_{\mathrm{A}}$ – the current density in medium A (air) at the discontinuity boundary of resistivity,

$\boldsymbol{J}_{\mathrm{B}}$ – the current density in medium B (upper soil layer) at the discontinuity boundary of resistivity,

$\boldsymbol{J}_{\mathrm{C}}$ – the current density in medium C (lower soil layer) at the discontinuity boundary of resistivity.

Air (medium A) has high resistivity and it thought to be 10^{18} Ω·m. Knowing the boundary conditions (1) and (2) at the discontinuity boundary of resistivity facilitates the mathematical solution of the task and the determination of the voltage on the potential measurement electrodes (Figure 4). This task is most frequently solved by applying the method of images to the discontinuity boundary of resistivity. Using the method of images, i.e. current electrodes at the soil–air boundary and the boundary between the upper and lower soil layers, with the simultaneous replacement of rod electrodes with suitable spherical electrodes, equations for the boundary conditions are satisfied: (1) and (2), the procedure for is described in more detail in [4] and [5]. The first image charge is at the soil–air boundary, where the half sphere of the equivalent rod electrode is imaged on the half sphere in medium A, as shown in Figure 4. This is followed by image charges of the spheres A and D from the boundary of the upper and lower soil layers. Then the obtained image from the lower soil layer is imaged from the soil–air boundary, after which the procedure is repeated. More can be learned about the application of the method of image charges in multilayer soil in [6], and about the interpretation of the obtained values and measurement data in [7] and [8].



Slika 4
Odslikavanje u dvoslojnom tlu i Wennerov raspored elektroda

Figure 4
Image charges in two-layer soil and the Wenner electrode arrangement

Potencijal u središtu naponske elektrode B zbog struja elektroda A i D iznosi:

The potential in the center of the potential electrode B caused by the current in electrodes A and D equals:

$$\underline{\varphi}_{B} = (2\underline{I})\frac{\rho_{E}}{4\pi}\left(\frac{1}{a}-\frac{1}{2a}\right) = (2\underline{I})\frac{\rho_{E}}{4\pi}\left(\frac{1}{2a}\right). \tag{3}$$

Vrijednost struje je dvostruka ($2\underline{I}$), jer se originalna polukugla iz koje istječe struja I stopila sa svojom slikom, koja je također polukugla, a iz koje istječe struja $\underline{I}$. Potencijal u središtu naponske elektrode B, uz uvažavanje N odslikavanja elektroda od granica diskontinuiteta specifičnog električnog otpora glasi:

The current value is double ($2\underline{I}$), because the original half sphere from which current I flows unites with its image, which is also half spherical, and from which current $\underline{I}$ flows. The potential in the center of the potential electrode B, taking into account N electrodes image charges from the discontinuity boundary of resistivity, is:

$$\underline{\varphi}_{B} = \frac{\underline{I}\rho_{E}}{2\pi}\left[\frac{1}{2a} + \sum_{n=1}^{N}\left(\frac{2\beta^{n}}{\sqrt{a^{2}+(2hn)^{2}}} - \frac{2\beta^{n}}{\sqrt{(2a)^{2}+(2hn)^{2}}}\right)\right]. \tag{4}$$

Izlučivanjem člana $1/a$ dobiva se:

By extracting $1/a$, the following is obtained:

$$\underline{\varphi}_{B} = \frac{\underline{I}\rho_{E}}{2\pi}\frac{1}{a}\left[\frac{1}{2} + \sum_{n=1}^{N}\left(\frac{2\beta^{n}}{\sqrt{1+\left(\frac{2hn}{a}\right)^{2}}} - \frac{2\beta^{n}}{\sqrt{4+\left(\frac{2hn}{a}\right)^{2}}}\right)\right]. \tag{5}$$

Kako je $\varphi_{B} = -\varphi_{C}$, zbog simetrije (slika 4) napon U_{BC} iznosi $U_{BC} = 2\varphi_{B}$, te napon između elektroda B i C uzrokovan strujom $\underline{I}$ glasi:

Since $\varphi_{B} = -\varphi_{C}$, due to symmetry (Figure 4), the voltage U_{BC} is: $U_{BC} = 2\varphi_{B}$, and the voltage between electrodes B and C caused by the current $\underline{I}$ is:

$$\underline{U}_{BC} = \frac{\underline{I}\rho_{E}}{2\pi}\frac{1}{a}\left[1 + \sum_{n=1}^{N}\left(\frac{4\beta^{n}}{\sqrt{1+\left(\frac{2hn}{a}\right)^{2}}} - \frac{4\beta^{n}}{\sqrt{4+\left(\frac{2hn}{a}\right)^{2}}}\right)\right]. \tag{6}$$

Prividni specifični otpor prema Wennerov rasporedu elektroda određuje se izrazom:

Apparent resistivity according to the Wenner electrode arrangement is determined by the following expression:

$$\rho_{\mathrm{PRIVIDNO/APPARENT}}(a) = 2\pi a\frac{U_{V}}{I} = 2\pi a\frac{U_{BC}}{I}. \tag{7}$$

Kako su udaljenosti odslikanih izvora polja od granice tlo–zrak: $2h, 4h, 6h,...$ lako se određuje opći izraz za prividni specifični otpor tla za uvaženih N slika, a koji glasi:

Since the distances of image charges from the soil–air boundary are $2h, 4h, 6h,...$ it is easy to determine the general expression for apparent soil resistivity, taking into account N image charges, as follows:

$$\rho_{\mathrm{PRIVIDNO/APPARENT}}(a)=\rho_g\left[1+4\cdot\sum_{n=1}^{N}\beta^n\left(\left(1+\left(n\cdot\frac{2h}{a}\right)^2\right)^{-\frac{1}{2}}-\left(4+\left(n\cdot\frac{2h}{a}\right)^2\right)^{-\frac{1}{2}}\right)\right], \tag{8}$$

u kojemu se koeficijent refleksije β računa izrazom:

in which the reflection coefficient β is calculated using the expression:

$$\beta=\frac{\rho_d-\rho_g}{\rho_d+\rho_g}. \tag{9}$$

Kada bi mjerenje bilo idealno, tada bi se prividni specifični otpor određivao usporedbom mjernih rezultata dobivenih prema (7) s teorijskim modelom prema (8) ili grafički s prikladnim krivuljama [6]. Međutim, kako se mjerenje obavlja u blizini VN nadzemnog voda potrebno je odrediti njegov utjecaj na mjerenje.

If measurement were ideal, the apparent soil resistivity would be determined by comparing the measured results obtained according to (7) to the theoretical model according to (8) or graphically using suitable curves according to [6]. However, since measurement is performed in the vicinity of a high voltage overhead transmission line, it is necessary to determine its influence upon the measurement.

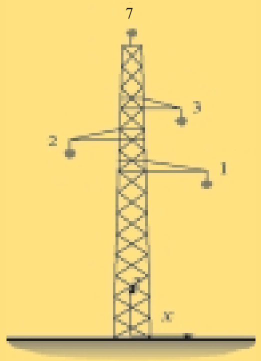
3 UTJECAJ VN NADZEMNOG VODA NA MJERENJE SPECIFIČNOG OTPORA TLA

Utjecaj VN nadzemnog voda na mjerenje specifičnog otpora tla najlakše je analizirati na primjeru koji se javlja u praksi. Kao primjer neka posluži mjerenje u blizini VN nadzemnog voda, u kojemu su fazni vodiči na dalekovodnom stupu u žargonu zvanom jela. Podaci o koordinatama s presjekom faznih vodiča i zaštitnog užeta za čelično rešetkasti stup sažeti su u tablici 1.

3 THE INFLUENCE OF A HIGH VOLTAGE OVERHEAD TRANSMISSION LINE ON THE MEASUREMENT OF SOIL RESISTIVITY

The influence of a high voltage overhead transmission line on the measurement of specific ground resistance can be analyzed most easily using an example that occurs in practice. For the example, we can use measurement in the vicinity of a high voltage overhead transmission line, with the phase conductors on the transmission tower, known as "Fir". The data on the coordinates and the cross section of the phase conductors and ground wire on the steel tower are summarized in Table 1.

Tablica 1 – Čelično rešetkasti stup i prostorni razmještaj vodiča
Table 1 – Steel tower and the coordinates of the conductors

	Vodič / Conductor	1	2	3	7
	Koordinata / Coordinate x (m)	3,511	–2,989	2,511	0
	Koordinata / Coordinate z (m)	29,75	31,95	34,15	38,90
	Vanjski radijus / Outside radius (cm)	1,095	1,095	1,095	0,8
	Fazni vodiči / Phase conductor	240/40 Al/Fe Radijus jezgre / Core radius: 0,4 cm Radijus Al žice / Al wire radius: 0,1725 cm Broj Al žica / Number of Al wires: 26 žica / wires			
	Zaštitni vodič / Ground wire	Radijus jezgre / Core radius: 0,48 cm Radijus Al žice / Al wire radius: 0,16 cm Broj Al žica / Number of Al wires: 12 žica / wires			

Dozemni kapacitet [5] ravnog dugog cilindričnog vodiča duljine l_v i radijusa r_v, koji se nalazi na visini h_v iznad tla iznosi:

Ground capacitance [5] of a straight long cylindrical conductor (length = l_v, radius = r_v, and height = h_v above the soil surface) is as follows:

$$C_V = \frac{2\pi\varepsilon_0 \cdot l_V}{\ln\dfrac{2h_V}{r_V}}\,. \tag{10}$$

Potencijal točke u prostoru, koja se nalazi na radijalnoj udaljenosti r od aksijalne osi ravnog dugog cilindričnog vodiča prema [5] iznosi:

The potential of a point in space located at the radial distance r from the axis of the straight long cylindrical conductor according to [5] equals:

$$\varphi(r) = \frac{\lambda}{2\pi\varepsilon_0}\ln\frac{r_V}{r}\,, \tag{11}$$

gdje je λ linijska gustoća naboja na vodiču (As/m).

where λ is the linear charge density on a conductor (As/m).

Skalarni električni potencijali u prostoru iznad tla ($z \geq 0$), zbog linijskih gustoća naboja na vodičima faza R, S i T i njihovih slika ispod tla prema jednadžbi (11) glase:

Electrical scalar potentials in the space above the soil surface ($z \geq 0$), due to the linear charge density on the phase conductors R,S and T and their images below the soil surface according to equation (11) are as follows:

$$\underline{\varphi}_R(x,z) = \frac{\underline{\lambda}_R}{2\pi\varepsilon}\left[\ln\frac{r_V}{\sqrt{(x_R-x)^2+(z_R-z)^2}} - \ln\frac{r_V}{\sqrt{(x_R-x)^2+(z_R+z)^2}}\right], \tag{12}$$

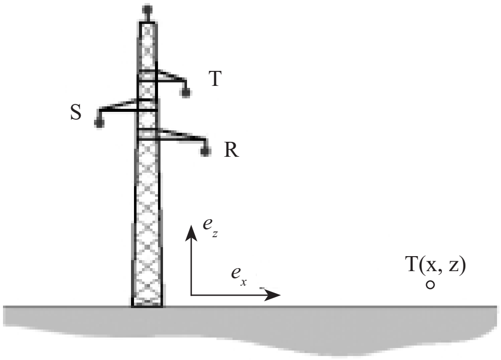
$$\underline{\varphi}_S(x,z) = \frac{\underline{\lambda}_S}{2\pi\varepsilon}\left[\ln\frac{r_V}{\sqrt{(x_S-x)^2+(z_S-z)^2}} - \ln\frac{r_V}{\sqrt{(x_S-x)^2+(z_S+z)^2}}\right], \tag{13}$$

$$\underline{\varphi}_T(x,z) = \frac{\underline{\lambda}_T}{2\pi\varepsilon}\left[\ln\frac{r_V}{\sqrt{(x_T-x)^2+(z_T-z)^2}} - \ln\frac{r_V}{\sqrt{(x_T-x)^2+(z_T+z)^2}}\right]. \tag{14}$$

Potencijal točke promatranja $\mathrm{T}(x,z)$ (slika 5), zbog linijskih gustoća naboja na fazama R, S i T, i njihovih slika ispod granice tlo–zrak iznosi:

The potential of the point $\mathrm{T}(x,z)$ (Figure 5), due to the linear charge density on the phase conductors R, S and T, and their images below the soil–air boundary equals:

$$\underline{\varphi}(x,z) = \underline{\varphi}_R(x,z) + \underline{\varphi}_S(x,z) + \underline{\varphi}_T(x,z)\,. \tag{15}$$



Slika 5
Raspored faznih vodiča i relevantna geometrija

Figure 5
Arrangement of phase conductors and the relevant geometry

Uzme li se da sve tri faze imaju približno jednak kapacitet koji iznosi C_V, tada iz relacije građe $q_V = C_V \cdot u$, uz $q_V = \lambda_V \cdot l_V$ slijede linijske gustoće naboja na vodičima faza R, S i T:

Assuming that all three phases have approximately equal capacities, C_V, then from $q_V = C_V \cdot u$, and $q_V = \lambda_V \cdot l_V$, the linear charge densities at the phase conductors R, S and T are as follows:

$$\underline{\lambda}_R = \underline{\varphi}_R \frac{2\pi\varepsilon_0}{\ln\frac{2h_{V,SR}}{r_V}}, \quad \underline{\lambda}_S = \underline{\varphi}_S \frac{2\pi\varepsilon_0}{\ln\frac{2h_{V,SR}}{r_V}}, \quad \underline{\lambda}_T = \underline{\varphi}_T \frac{2\pi\varepsilon_0}{\ln\frac{2h_{V,SR}}{r_V}}, \qquad (16)$$

gdje je $h_{V,SR}$ srednja geometrijska visina vodiča faza R, S i T.

where $h_{V,SR}$ is the mean geometric height of the phase conductors R, S and T.

Uvrštavanjem linijskih gustoća struje $\underline{\lambda}_R$, $\underline{\lambda}_S$ i $\underline{\lambda}_T$ prema izrazu (16) u jednadžbe (12), (13) i (14) izraz za potencijal (15) može se napisati u obliku:

Inserting linear charge densities $\underline{\lambda}_R$, $\underline{\lambda}_S$, and $\underline{\lambda}_T$ according to (16) in equations (12), (13) and (14), the expression for potential (15) can be written in the following form:

$$\underline{\varphi}(x,z) = K\left(\underline{\varphi}_R \ln\frac{\sqrt{(x_R-x)^2+(z_R+z)^2}}{\sqrt{(x_R-x)^2+(z_R-z)^2}} + \underline{\varphi}_S \ln\frac{\sqrt{(x_S-x)^2+(z_S+z)^2}}{\sqrt{(x_S-x)^2+(z_S-z)^2}} + \underline{\varphi}_T \ln\frac{\sqrt{(x_T-x)^2+(z_T+z)^2}}{\sqrt{(x_T-x)^2+(z_T-z)^2}}\right), \qquad (17)$$

u kojemu je:

where:

$$K = \frac{1}{\ln\frac{2h_{V,SR}}{r_V}}, \qquad (18)$$

Fazni naponi vodiča faza: R, S i T u fazorskoj notaciji, a iskazani u polarnom obliku glase $\underline{\varphi}_R = U_f \angle 0^\circ$ V, $\underline{\varphi}_S = U_f \angle 120^\circ$ V, $\underline{\varphi}_T = U_f \angle 240^\circ$ V, odnosno u algebarskom obliku $\underline{\varphi}_R = U_f\,(1+j0)$ V, $\underline{\varphi}_S = U_f\,(-0.5+j0,866)$ V, $\underline{\varphi}_T = U_f\,(-0.5-j0,866)$ V. Korištenje algebarskog oblika faznih napona omogućava rastavljanje izraza (17) na realni i imaginarni dio:

The phase conductor voltages R, S and T in phasor notation, and expressed in polar form are $\underline{\varphi}_R = U_f \angle 0^\circ$ V, $\underline{\varphi}_S = U_f \angle 120^\circ$ V, $\underline{\varphi}_T = U_f \angle 240^\circ$ V, or in algebraic form are $\underline{\varphi}_R = U_f\,(1+j0)$ V, $\underline{\varphi}_S = U_f\,(-0.5+j0,866)$ V, $\underline{\varphi}_T = U_f\,(-0.5-j0,866)$ V. Expressing phase voltages in algebraic form, the equation (17) can be separated into its real and imaginary parts:

$$\mathrm{Re}\,\underline{\varphi}(x,z)=U_f\,\frac{K}{2}\left(\ln\frac{(x_R-x)^2+(z_R+z)^2}{(x_R-x)^2+(z_R-z)^2}-0,5\cdot\ln\frac{(x_S-x)^2+(z_S+z)^2}{(x_S-x)^2+(z_S-z)^2}-0,5\cdot\ln\frac{(x_T-x)^2+(z_T+z)^2}{(x_T-x)^2+(z_T-z)^2}\right), \qquad (19)$$

$$\mathrm{Im}\,\underline{\varphi}(x,z)=U_f\,\frac{K}{2}\left(0,866\cdot\ln\frac{(x_S-x)^2+(z_S+z)^2}{(x_S-x)^2+(z_S-z)^2}-0,866\cdot\frac{(x_T-x)^2+(z_T+z)^2}{(x_T-x)^2+(z_T-z)^2}\right). \qquad (20)$$

Za razliku od teorijskog modela u kojemu je granica tlo–zrak predstavljena ravninom, površina tla je neravna, ujedno i najčešće prekrivena niskim raslinjem. U takvim uvjetima položeni vodiči ožičenja mjernog spoja teorijski ne leže na granici tlo–zrak, koja je na nultom potencijalu, nego su od nje odmaknuti. Arbitražno se može usvojiti da je pomak od 1 do 2 cm. U tom slučaju vodiči ožičenja doći će na neki potencijal u odnosu na referentu nul-točku. S obzirom da će vodiči naponskih grana između voltmetra i elektrode B, odnosno C, doći na različite potencijale, javit će se napon koji će predstavljati mjernu smetnju. U slučaju kada je raspored mjernih elektroda duž pravca okomitog na trasu dalekovoda, tada srednji potencijal vodiča duljine l, a kojemu je središte udaljeno od trase dalekovoda za s (slika 2) iznosi:

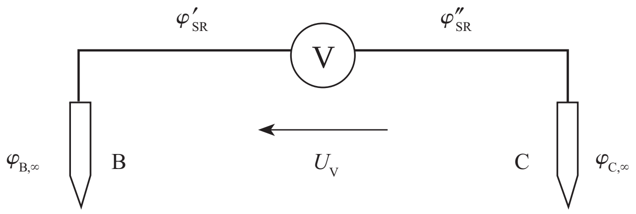
Unlike the theoretical model in which the soil–air boundary is represented by a plane, the soil surface is uneven and also most frequently covered by low vegetation. Under such conditions, the measurement leads are theoretically not placed at the soil–air boundary, which is at the zero potential, but are placed away from it. Arbitrarily, it is accepted that this space ranges from 1 cm to 2 cm. In this case, the measurement leads will reach a potential in relation to the reference zero-point. Since the measurement leads between the voltmeter and electrode B or C will be at different potentials, voltage will occur which represents measurement interference. In the event that the spacing of the measurement electrodes is along a line perpendicular to the route of the transmission line, then the mean potential of the conductor of length l, whose center is at a distance s from the transmission line route (Figure 2), equals:

$$\underline{\varphi}_{SR}=\frac{1}{l}\int_0^l\underline{\varphi}(x,z)\mathrm{d}x\,. \qquad (21)$$

Na slici 6 prikazana je naponska mjerna grana Wennerovog spoja s prikazanim potencijalima ožičenja i mjernih elektroda.

Figure 6 shows a potential measurement circuit using the Wenner method with the potentials of the leads and the measuring electrodes indicated.

Slika 6
Naponska mjerna grana, potencijali ožičenja i mjernih elektroda
Figure 6
Potential measurement circuit, measurement leads and electrode potentials



Prema slici 6 voltmetar s naznačenim referentnim smjernom napona mjeri napon:

According to Figure 6, a voltmeter with the indicated voltage reference direction measures voltage as follows:

$$\underline{U}_{\mathrm{V}} = \left(\underline{\varphi}_{\mathrm{B},\infty} + \underline{\varphi}'_{\mathrm{SR}}\right) - \left(\underline{\varphi}_{\mathrm{C},\infty} + \underline{\varphi}''_{\mathrm{SR}}\right) = \underline{U}_{\mathrm{BC}} + \left(\underline{\varphi}'_{\mathrm{SR}} - \underline{\varphi}''_{\mathrm{SR}}\right) = \underline{U}_{\mathrm{BC}} + \underline{U}_{\text{šuma/noise}} \,. \tag{22}$$

Srednji potencijal vodiča između voltmetra i elektrode B označen je sa $\underline{\varphi}'_{\mathrm{SR}}$, a između voltmetra i elektrode C sa $\underline{\varphi}''_{\mathrm{SR}}$. Srednji potencijali vodiča ožičenja $\underline{\varphi}'_{\mathrm{SR}}$, $\underline{\varphi}''_{\mathrm{SR}}$ određuju se izrazima:

The mean potential of the conductor between the voltmeter and electrode B is indicated by $\underline{\varphi}'_{\mathrm{SR}}$, and between the voltmeter and electrode C by $\underline{\varphi}''_{\mathrm{SR}}$. The mean potentials of the conductor indicated by $\underline{\varphi}'_{\mathrm{SR}}$, $\underline{\varphi}''_{\mathrm{SR}}$ are determined by the following expressions:

$$\underline{\varphi}'_{\mathrm{SR}} = \frac{2}{a} \int_{s-a/2}^{s} \underline{\varphi}(x,z)\mathrm{d}x \,, \quad \underline{\varphi}''_{\mathrm{SR}} = \frac{2}{a} \int_{s}^{s+a/2} \underline{\varphi}(x,z)\mathrm{d}x \,. \tag{23}$$

Kako su napon između mjernih elektroda $\underline{U}_{\mathrm{BC}}$ i napon $\underline{U}_{\text{šuma/noise}}$ različitih frekvencija, efektivna vrijednost izmjerenog napona bez korištenja filtra kojim se napon smetnje prigušuje iznosi:

Since the voltage between the measuring electrodes $\underline{U}_{\mathrm{BC}}$ and the noise voltage $\underline{U}_{\text{šuma/noise}}$ are of different frequencies, the effective value of the measured voltage without the use of a filter that attenuates the voltage equals:

$$U_{\mathrm{V}} = \sqrt{U_{\mathrm{BC}}^{2} + U_{\text{šuma/noise}}^{2}} \,. \tag{24}$$

Napon U_{BC} određuje se izrazom (6). Prividni specifični otpor tla prema (7) iznosi:

Voltage U_{BC} is determined with the expression (6). The apparent soil resistivity according to (7) equals:

$$\begin{aligned} \rho_{\text{PRIVIDNO/APPARENT}}(a) &= 2\pi a \frac{U_{\mathrm{V}}}{I} = \sqrt{\frac{4\pi^{2} a^{2}}{I^{2}} \left(U_{\mathrm{BC}}^{2} + U_{\text{šuma/noise}}^{2}\right)} \\ &= \sqrt{\rho_{\text{PRIVIDNO/APPARENT, stvarno/real}}^{2}(a) + \rho_{\text{PRIVIDNO/APPARENT, šuma/noise}}^{2}(a)} \end{aligned} \,. \tag{25}$$

Komponenta koja izaziva pogrešku mjerenja prividnog specifičnog otpora $\rho_{\text{PRIVIDNO/APPARENT, šuma/noise}}(a)$ glasi:

The component that causes an error in the measurement of the apparent soil resistivity $\rho_{\text{PRIVIDNO/APPARENT, šuma/noise}}(a)$ is as follows:

$$\rho_{\text{PRIVIDNO/APPARENT, šuma/noise}}(a) = \frac{2\pi a}{I} U_{\text{šuma/noise}} = \frac{2\pi a}{I} \left| \underline{\varphi}'_{\mathrm{SR}} - \underline{\varphi}''_{\mathrm{SR}} \right| \,. \tag{26}$$

Utjecaj napona šuma kao mjerne smetnje **inverzno je proporcionalan mjernoj struji**. Dobiveni izraz ukazuje na način na koji se kapacitivni utjecaj faza VN nadzemnih vodova može smanjiti pri mjerenju specifičnog otpora tla. Prema dobivenom izrazu mjerenje specifičnog otpora tla treba obavljati sa što većom mjernom strujom, ukoliko se mjerenje obavlja u blizini izvora EM zračenja. Granica maksimalno dozvoljene struje koja se smije koristiti pri mjerenju određena je sigurnosnim

The effect of noise voltage as measurement noise is **inversely proportional to measurement current**. The expression obtained demonstrates the manner in which the capacitive influence of high voltage overhead transmission lines can be reduced during the measurement of soil resistivity. According to the expression obtained, the measurement of soil resistivity should be performed with the maximum measurement current, if measurement is performed in the vicinity of a source of electromagnetic radiation. The maximum permissible current mjerama, odnosno dozvoljenim naponom dodira (50 V), i mogućnošću mjernog uređaja da osigura željeni iznos struje.

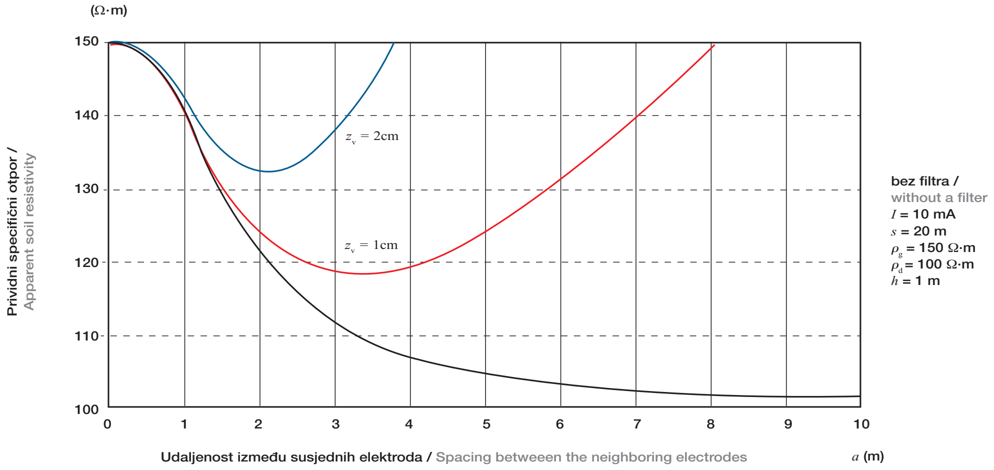
4 NUMERIČKI PRIMJERI

Primjenu dobivenih izraza najlakše je prikazati numeričkim primjerom. Neka je specifični električni otpor gornjeg sloja tla $\rho_g = 150\ \Omega\cdot$m i debljine $h = 1$ m, a donjeg $\rho_d = 100\ \Omega\cdot$m. Udaljenost središta mjernog spoja od trase dalekovoda iznosi $s = 20$ m. Mjerenje specifičnog otpora tla obavlja se sa strujom od $I = 10$ mA, s uređajem bez filtra, kojim se prigušuje napon smetnji od 50 Hz. Na slici 7 prikazane su krivulje prividnog specifičnog otpora tla dobivene pod različitim pretpostavkama. Crna krivulja odnosi se na idealni slučaj kada ne postoje mjerne smetnje, a dobivena je prema jednadžbi (8). Navedena krivulja je referentna. Ostale dvije krivulje dobivene su korištenjem jednadžbe (25), a odnose se na slučajeve kada su vodiči ožičenja naponske grane pomaknuti od granice tlo–zrak za 1cm i 2 cm. Obje krivulje odnose se na slučaj kada se mjerenje obavlja s mjernim instrumentom bez filtra kojim se prigušuje mjerna smetnja, tj. napon frekvencije 50 Hz.

that may be used during measurement is determined by safety measures, i.e. the permissible touch voltage (50 V), and the ability of the measuring device to provide the desired amount of current.

4 NUMERICAL EXAMPLES

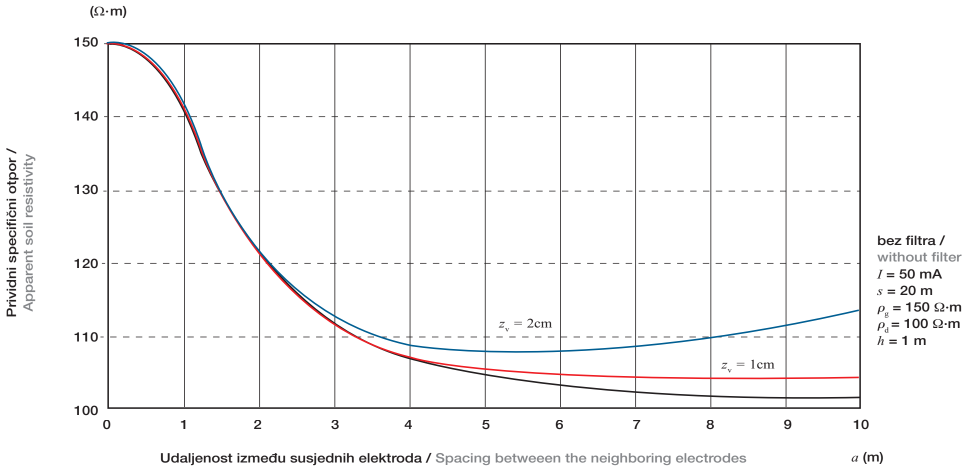
The application of the expressions obtained can most easily be presented by using a numerical example. Let the resistivity of the upper soil layer be $\rho_g = 150\ \Omega\cdot$m and the thickness $h = 1$ m, and of the resistivity of the lower layer $\rho_d = 100\ \Omega\cdot$m. The distance between the center of the measurement circuit and the route of the transmission line is $s = 20$ m. Measurement of soil resistivity is performed with a current of $I = 10$ mA, using an instrument without a filter for the attenuation of the noise voltage of 50 Hz. In Figure 7, the curves of apparent soil resistivity are presented that are obtained under different assumptions. The black curve refers to the ideal case when there is no measurement noise and is obtained according to equation (8). This is the reference curve. The other two curves were obtained using equation (25), and refer to cases when the leads of the potential measurement circuit were raised from the soil–air boundary by 1 and 2 cm. Both curves refer to the case when the measurement is performed using a measuring instrument without a filter for the attenuation of the noise, i.e. voltage of 50 Hz.



Slika 7
Prividni specifični otpor tla
Figure 7
Apparent soil resistivity

Utjecaj povećanja mjerne struje I na određivanje prividnog specifičnog otpora tla prikazan je na slici 8. U navedenom slučaju također je pretpostavljeno da se mjerenje obavlja s mjernim uređajem bez filtra kojim se prigušuje napon frekvencije 50 Hz, ali je mjerna struja povećana sa 10 mA (slika 7) na 50 mA.

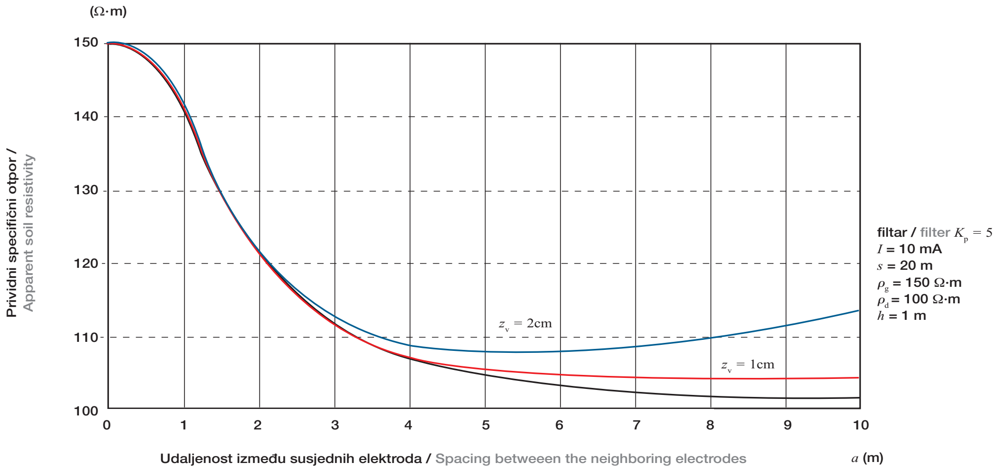
The effect that an increase in the measurement current I has on the apparent soil resistivity is shown in Figure 8. In this case, it is also assumed that measurement is performed with a measuring instrument without a filter for the attenuation of the noise voltage of 50 Hz, but the measurement current is increased from 10 mA (Figure 7) to 50 mA.



Slika 8
Prividni specifični otpor tla
Figure 8
Apparent soil resistivity

Utjecaj filtra kojim se prigušuje smetnja, tj. mjerni napon frekvencije 50 Hz s koeficijentom prigušenja K_P = 5 prikazan je na slici 9. U navedenom primjeru mjerenje se obavlja mjernom strujom od 10 mA.

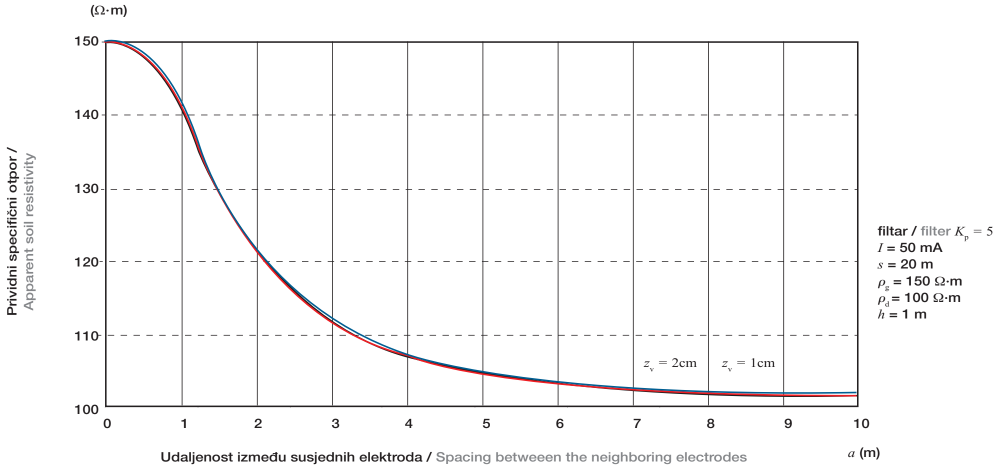
The effect of a filter used to attenuate the noise, i.e. the measurement voltage of 50 Hz with the attenuation coefficient $K_P = 5$ is shown in Figure 9. In this example, measurement is performed with the measurement current of 10 mA.



Slika 9
Prividni specifični otpor tla
Figure 9
Apparent soil resistivity

Utjecaj filtriranja mjernog signala (mjernog napona) naponske grane mjernog spoja s istodobnom povećanom mjernom strujom prikazan je na slici 10. U navedenom slučaju mjerenje se obavlja mjernom strujom od 50 mA, a koeficijent prigušenja mjerne smetnje, tj. napona frekvencije 50 Hz iznosi $K_P = 5$.

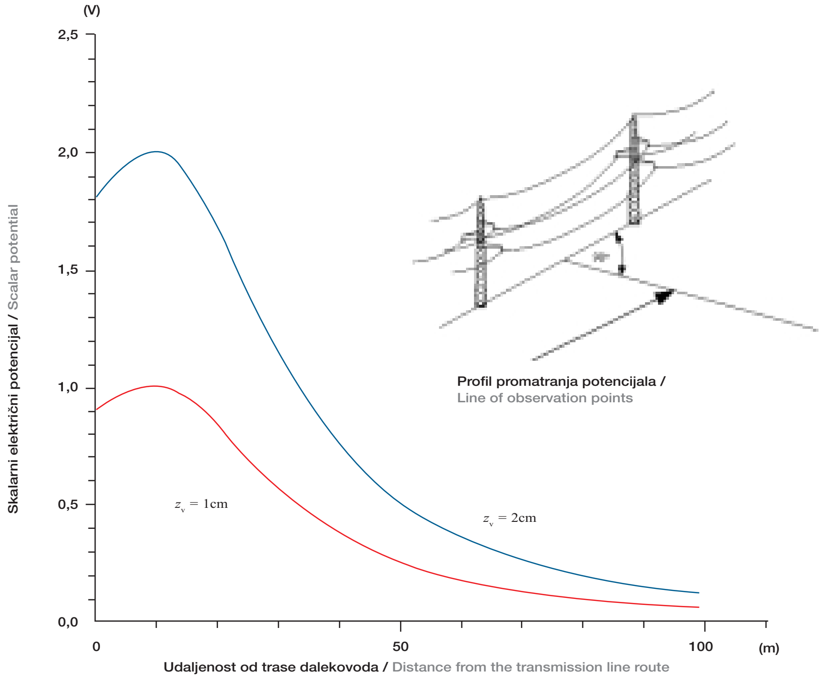
The effect of filtering the measurement signal (measurement voltage) of a potential measurement circuit with a simultaneous increase in the measurement current is presented in Figure 10. In this case, measurement is performed with the measurement current of 50 mA and the noise attenuation coefficient, i.e. the voltage of 50 Hz, is $K_P = 5$.



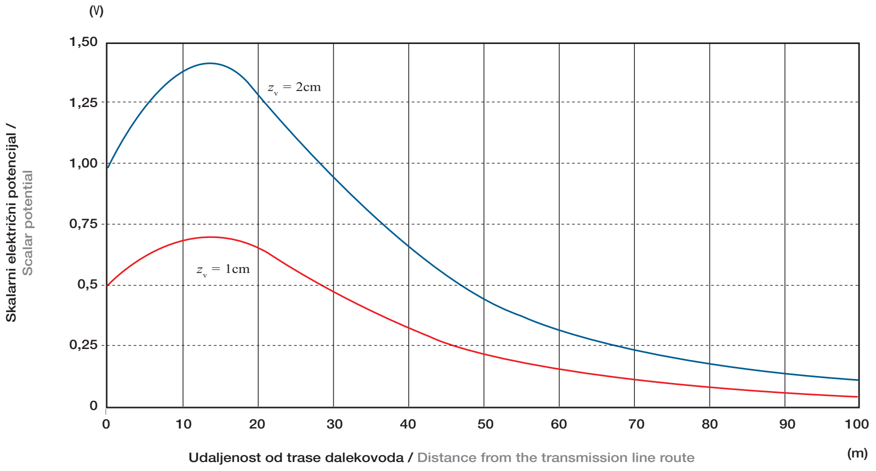
Slika 10
Prividni specifični otpor tla
Figure 10
Apparent soil resistivity

Kako je riječ o trofaznom sustavu, a kapacitet vodiča određen prema jednadžbi (10), to znači da je utjecaj međusobnih kapaciteta zanemaren. Iz tog razloga potrebno je provjeriti valjanost navedene aproksimacije. U tu svrhu skalarni električni potencijal duž profila točaka promatranja koje leže na pravcu okomitom na trasu dalekovoda, a koji se nalazi na visini od 1 cm i 2 cm od tla određen je pomoću prikazane teorije korištenjem programa Mathcad11 i profesionalnog programskog paketa CDEGS, koji za elektromagnetske zadaće koristi integralnu formulaciju polja, a za njezino numeričko rješavanje koristi metodu momenata. Rezultati oba pristupa prikazani su na slikama 11 i 12.

Since this concerns a three-phase system, when conductor capacity is determined according to equation (10), the effect of the mutual capacitance is negligible. For this reason, it is necessary to test the validity of the above-mentioned approximation. For this purpose, the scalar electrical potential along the line of observation points, which is perpendicular to the route of the transmission line and is located at heights of 1 cm and 2 cm above the soil, is determined by the presented theory using the program Mathcad11 and the professional program package CDEGS, which uses an integral field formulation for electromagnetic tasks and the method of moments for their numerical solution. The results of both approaches are presented in Figures 11 and 12.



Slika 11
Skalarni električni potencijal duž profila okomitog na trasu dalekovoda, a pomaknutog od tla za z_v = 1 cm i z_v = 2 cm.
Figure 11
Scalar potential along the line of observation points which is perpendicular to the route of the transmission line, and at a distance above the soil of z_v = 1 cm and z_v = 2 cm



Slika 12
Skalarni električni potencijal duž profila okomitog na trasu dalekovoda, a pomaknutog od tla za $z_v = 1$ cm i $z_v = 2$ cm – rezultat dobiven korištenjem programskog paketa MATHCAD11 prema jednadžbama (19) i (20).

Figure 12
Scalar potential along the line of observation points which is perpendicular to the route of the transmission line and at a distance above the soil of $z_v = 1$ cm and $z_v = 2$ cm – the results were obtained with the program MATHCAD11 according to equations (19) and (20).

5 ANALIZA REZULTATA

Kao što je to bilo i najavljeno, proračune potencijala duž profila točaka koji se nalaze na pravcu okomitom na trasu dalekovoda pomaknutom od granice tlo–zrak potrebno je provjeriti. U radu je na približan način određen navedeni potencijal jednadžbama (19) i (20). Slike 11 i 12 prikazuju potencijal duž točaka na navedenom profilu određen prikazanom teorijom (slika 12) i teorijom polja dobivenom na međunarodnoj razini priznatim programskim alatom CDEGS (slika 11). Rezultati dobivene programskim paketom CDEGS mogu se smatrati referentnim. Uspoređujući slike 11 i 12 zapaža se razlika od 20-ak posto što je prihvatljiva aproksimacija. Iz tog razloga rezultati prikazanom teorijom su valjani. Uspoređujući sliku 8 sa slikom 9 zapaža se da je utjecaj filtriranja ulaznog signala istovjetan s povećanjem mjerne struje. Naime, povećanje mjerne struje sa 10 mA (slika 7) na 50 mA (slika 8) prema jednadžbi (26) smanjuje pogreške jednako kao i da se napon smetnje prigušio filtrom s koeficijentom prigušenja od $K_p = 5$. Teorijski predviđen blagodatan utjecaj povećanja mjerne struje na smanjenje mjerne pogreške prema jednadžbi (26) time je potvrđen. Istodobnim povećanjem mjerne struje s filtriranjem mjernog napona (slika 10) moguće je u potpunosti prigušiti mjernu smetnju, te obaviti mjerenje u blizini VN objekata. Slike 7 do 10 ukazuju na činjenicu da pri mjerenju specifičnog otpora tla u blizini VN dalekovoda treba nastojati da se vodiči ožičenja nalaze što bliže tlu, kako bi se nalazili u ravnini nultog potencijala. Polaganje kabela preko niskog raslinja i grmova trebalo bi svakako izbjegavati, jer bi se na taj način pogreška pri mjerenju znatno povećala.

5 ANALYSIS OF RESULTS

As stated, the results of the calculation of the potential along the line of observation points which is perpendicular to the route of the transmission line and raised above the earth–air boundary must be validated. In this paper, the potential is approximately determined from the equations (19) and (20). Figures 11 and 12 show the potential along the line of observation points determined by the presented theory (Figure 12), and the field theory obtained at the international level by the software program CDEGS (Figure 11). The results obtained with the software program CDEGS may be considered as reference results. Comparing Figures 11 and 12, a difference is noted of approximately 20 %, which is an acceptable approximation. For this reason, the results presented according to the theory are valid. Comparing Figure 8 to Figure 9, it is noted that the effect of filtering the input signal is equal to the increase of the measurement current. The increase of the measurement current from 10 mA (Figure 7) to 50 mA (Figure 8) according to equation (26) reduces the error equally as if the noise voltage were attenuated with a filter that has an attenuation coefficient of $K_p = 5$. The theoretically assumed positive effect that the increase of the measurement current has on the decrease of the measurement error according to equation (26) is thereby confirmed. The simultaneous increase in measurement current and the filtering of the measurement voltage (Figure 10) can completely attenuate measurement noise. Therefore, measurements in the vicinity of high voltage objects can be performed. Figures 7 to 10 demonstrate the fact that when measuring soil resistivity in the vicinity of a high voltage transmission line, it is necessary for the measurement leads to be located as close to the soil as possible, in order for them to be at the zero potential plane. The laying of leads through low vegetation and bushes should certainly be avoided because this significantly increases measurement errors.

6 ZAKLJUČAK

U radu je prikazan najjednostavniji mogući model utjecaja VN nadzemnih vodova na mjerenje specifičnog otpora tla. Na jednostavan način prikazan je utjecaj kapacitivne veze između VN nadzemnih vodova i naponske grane ožičenja Wennerovog mjernog spoja. Na taj način inženjerima u praksi omogućeno je modeliranje navedenog utjecaja poznavajući struju mjerenja i koeficijent prigušenja napona smetnje od 50 Hz mjernog uređaja. Model se pokazao valjanim i zadovoljavajuće točnim za navedenu analizu. Pomoću prikazanog modela moguće je definirati potrebe pri dizajniranju filtara, utjecaja mjerne struje na točnost mjerenja. Prikazan model omogućuje analizu utjecaja visine položenih vodiča ožičenja naponske mjerne grane na točnost mjerenja. Iako je u članku prikazan utjecaj VN nadzemnih vodova na mjerenje specifičnog otpora tla, na jednak način se može modelirati utjecaj VN nadzemnih vodova na telekomunikacijske kabele. Osim navedene problematike i električna mjerenja otpora rasprostiranja uzemljivača pogođena su utjecajem smetnji i okoline, što iziskuje korekcije u proračunima [9].

6 CONCLUSION

This article presents the simplest possible model of the effect of high voltage overhead transmission lines on the measurement of soil resistivity. The effect of capacitive coupling between overhead transmission lines and the potential circuit of a Wenner electrode arrangement is presented in a simple manner, which allows engineers to model the stated effect if they know the measurement current and the attenuation coefficient of the 50 Hz noise voltage of the measuring device. This model has been shown to be valid and sufficiently precise for such analysis. Using the presented model, it is possible to define the design parameters for the filter and the effect of the measurement current on the measurement accuracy. The model presented facilitates the analysis of the effect of the height of the measurement leads of the potential measurement circuit on the precision of the measurement. Although the effect of high voltage overhead transmission lines on the measurement of soil resistivity is presented in this article, in the same manner it is possible to model the effect of high voltage overhead transmission lines on telecommunication cables. Furthermore, noise and the environment influence the measurement of ground resistance, necessitating the correction of calculations [9].

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Uredništvo primilo rukopis:
2007-02-13

Prihvaćeno:
2007-02-19

Manuscript received on:
2007-02-13

Accepted on:
2007-02-19