

NIKOLA KRSTIĆ¹
 DRAGAN TASIĆ²
 DARDAN
 KLIMENTA³

THE INFLUENCE OF GROUND WIRES ON THE RESISTANCE AND REACTANCE OF HIGH VOLTAGE OVERHEAD POWER LINES

^{1,2}University of Niš,
 Faculty of Electronic
 Engineering in Niš
³University of Priština in
 Kosovska Mitrovica,
 Faculty of Technical
 Sciences in Kosovska
 Mitrovica

¹nikola.krstic@elfak.ni.ac.rs
²dragan.tasic@elfak.ni.ac.rs
³dardan.klimenta@pr.ac.rs

Abstract: In this paper, the influence of ground wires on the resistance and reactance (longitudinal impedance) of high voltage overhead power lines (OPLs) is considered and the method for its calculation is described in detail. This is important considering the power flow calculation and the design of the protection system of OPLs, especially those which use distance relays. In addition to symmetric, asymmetric operating conditions of OPLs are also studied, for the analysis of which symmetric components are used. Specifically, this meant the calculation of longitudinal impedances of OPL for positive, negative and zero sequences in each considered case. Special attention is paid to the symmetric system with zero sequences, because the influence of ground wires on the change of longitudinal impedance of OPLs is the greatest in that case. The cases of OPLs with one (110 kV OPL) and two (400 kV OPL) ground wires are considered, using the values of their parameters that can be found in real systems. Values of longitudinal impedances, obtained with and without ground wires influence or the influence of some of their parameters, are compared, based on which appropriate conclusion is made.

Key words: ground wire, overhead power line (OPL), symmetric components, longitudinal impedance.

INTRODUCTION

Ground wires, instead of electricity transmission, have protective functions in power systems. These protective functions arise from the fact that ground wires are grounded on both sides via a metal structure and groundings of the poles. One of the main functions is the protection of conductors of overhead power lines (OPLs) from atmospheric discharges. Ground wires achieve this by being placed above the phase conductors of OPLs [1-2], which are thus located in the zones protected by them. In this manner, instead of a phase conductor atmospheric discharge hits the ground wires, and the overvoltage wave and current of the atmospheric discharge [3] are taken to the ground so that they least disturb the operating conditions of an OPL. This significantly reduces the number and intensity of high transient voltages in phase conductors, and thus the number of transient faults [4]. Another important protective function of ground wires is the reduction of fault current flowing through the ground. Namely, ground wires provide a parallel path for the currents during the faults with the ground and take the portion of fault current [5]. This reduces the voltage which appears in the grounding system and the surrounding soil during the fault.

In addition to their basic protection function, ground wires to a certain extent affect the values of electrical parameters of OPLs [6-7]. Specifically, this paper considers their influence on the longitudinal impedance, which includes the resistance and reactance of an OPL. Namely, due to the electromagnetic coupling between the phase conductors and the ground wires, as well as the

fact that the ground wires are grounded on both sides, a current is established in them. This current changes the total magnetic flux of phase conductors, and thus their longitudinal impedance. This effect is most pronounced in asymmetric operating conditions of OPLs [8], and especially in those cases where zero sequence currents appear in the phase conductors [9].

In order to find the current flowing through the ground wires, relationships for calculating the voltage of ground wires are used, where, in addition to the currents in the phase conductors and ground wires, their self and mutual impedances [10-11] also appear. By determining the current of ground wires, a reduced matrix of impedances is formed, which represents the connection between the phase voltages and the phase currents, taking into account the influence of ground wires. Asymmetric operating conditions are analyzed using symmetrical components [12] and by decomposing asymmetric into three symmetric systems, first, with positive, second, with negative, and, third, with zero phase sequence. For each of these three systems, the longitudinal impedances are determined as the main diagonal elements of the reduced impedance matrix in the symmetric component domain. Proper and precise determination of these impedances is very important [13-14], because based on them, a mathematical model for the analysis of OPLs under symmetric and asymmetric operating conditions is created. Mainly, this refers to power flow calculations, and the protection system design, where every change in the value of OPL longitudinal impedance that ground wires make, affects the operation and configuration of overcurrent and especially distance protective relays

[15] that are often used in protection systems of high voltage transmission networks.

This paper discusses the cases of OPLs with one and two ground wires (110 kV and 400 kV voltage level), compares the obtained values of longitudinal impedances for different cases, and based on that provides appropriate conclusions.

PROCEDURE FOR CALCULATING THE INFLUENCE OF GROUND WIRES

Impedance matrix in the symmetric component domain

Symmetric components represent a popular and frequently used method for analyzing the state of the power system described by the asymmetry of voltages and currents. This method decomposes the asymmetric into three symmetric systems, two three-phase systems with reverse-phase sequences, and one single-phase system with zero phase sequence. In this manner, the calculation is transferred from the phase quantities domain into the domain of the symmetric component and thus simplified. Upon returning from the symmetric components to the phase quantities domain, the transformation matrix $[T]$, is used, i.e.

$$[T] = \begin{bmatrix} 1 & 1 & 1 \\ e^{j\frac{4}{3}\pi} & e^{j\frac{2}{3}\pi} & 1 \\ e^{j\frac{2}{3}\pi} & e^{j\frac{4}{3}\pi} & 1 \end{bmatrix} \quad (1)$$

A matrix relationship that links the phase voltage vector \vec{V}_{abc} with the phase current vector \vec{I}_{abc} , is:

$$\vec{V}_{abc} = [Z_{abc}] \times \vec{I}_{abc} \quad (2)$$

where $[Z_{abc}]$ is impedance matrix in the phase domain. By transformation of the phase currents and voltages into the symmetric component domain, and by multiplying the left and right side of the relationship (2) with the inverse transformation matrix $[T]^{-1}$, the following can be obtained:

$$\vec{V}_{dio} = [T]^{-1} \times [Z_{abc}] \times [T] \times \vec{I}_{dio} \quad (3)$$

Based on the relationship (3), the impedance matrix in the symmetric component domain is:

$$[Z_{dio}] = [T]^{-1} \times [Z_{abc}] \times [T] \quad (4)$$

Determination of the longitudinal impedance of an OPL with ground wires

Longitudinal electrical parameters of OPLs with ground wires, which would enable modeling of OPLs not only for symmetric but also for asymmetric operating conditions, include the longitudinal impedance (resistance and reactance) for the positive, negative and zero phase sequences. In order to obtain these parameters, it is necessary to start from the matrix relationship that links voltages and currents in the phase domain, taking the influence of ground wires into

account. For the case of OPL with one ground wire this relationship can be written as:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ 0 \end{bmatrix} = \begin{bmatrix} Z_p & Z_{pp} & Z_{pp} & Z_{pg} \\ Z_{pp} & Z_p & Z_{pp} & Z_{pg} \\ Z_{pp} & Z_{pp} & Z_p & Z_{pg} \\ Z_{pg} & Z_{pg} & Z_{pg} & Z_g \end{bmatrix} \times \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_{gw} \end{bmatrix} \quad (5)$$

Where are: Z_p is the self-impedance of a phase conductor with ground return, Z_{pp} is the mutual impedance between two phase conductors, Z_{pg} is the mutual impedance between a phase conductor and the ground wire, and Z_g is the self-impedance of a ground wire with a ground return.

As can be seen from the relationship (5), the voltage of the ground wire is equal to zero because the ground wire is grounded on both sides. Also, the relationship (5) can only be applied in the case of the symmetrical arrangement of phase conductors or in the case when transposition is performed, which is usually done for high voltage OPLs. Accordingly, the same is assumed here. The elements of the impedance matrix are determined by means of the following relationships:

$$Z_p = R_p + R_g + j\omega L_p = R_p + R_g + j\omega \frac{\mu_0}{2\pi} \ln \frac{D_{ekv}}{r_{pe}} \quad (6)$$

$$Z_{pp} = R_g + j\omega M_{pp} = R_g + j\omega \frac{\mu_0}{2\pi} \ln \frac{D_{ekv}}{D} \quad (7)$$

$$Z_{pg} = R_g + j\omega M_{pg} = R_g + j\omega \frac{\mu_0}{2\pi} \ln \frac{D_{ekv}}{D_{pg}} \quad (8)$$

$$Z_g = R_{gw} + R_g + j\omega L_g = R_{gw} + R_g + j\omega \frac{\mu_0}{2\pi} \ln \frac{D_{ekv}}{r_{ge}} \quad (9)$$

where R_p is the resistance of one phase conductor, R_g is the resistance of a ground return path, R_{gw} is the resistance of the ground wire, L_p is the self-inductance of phase conductor with ground return, M_{pp} is the mutual inductance between any phase conductors, M_{pg} is the mutual inductance between phase conductors and the ground wires, L_g is the self-inductance of the ground wire with ground return, D_{ek} is the depth of an equivalent ground return path, r_{pe} is the equivalent radius of a phase conductor, D is the geometric mean distance between the phase conductors, D_{pg} is the geometric mean distance between the phase conductors and the ground wires, r_{ge} is the equivalent radius of the ground wire, μ_0 is the magnetic permeability of vacuum, ω is the angular frequency.

It must be pointed out that in all the previous relationships for determining the self and mutual impedances, the resistance of pole grounding is neglected (equal to zero).

In the case where more than one conductor is used per phase, instead of the equivalent radius of a phase conductor, an equivalent radius of a bundled phase conductor

$$r_{be} = \sqrt[n]{n \cdot R^{n-1} \cdot r_{pe}} \quad (10)$$

is used in all the previous relationships, where r_{pe} is the radius of the individual conductors in the bundle, R is the bundle radius of the symmetric set of conductors, and n is the number of conductors per phase.

The depth D_{ekv} and the resistance R_g of the equivalent path through the ground having the resistivity ρ_g at a frequency f are determined by:

$$D_{ekv} = 658.87 \sqrt{\frac{\rho_g}{f}} \quad [m] \quad (11)$$

$$R_g = \frac{\omega \mu_0}{8} \quad [\Omega/m] \quad (12)$$

Based on the relationship for the voltage of ground wire (5), the current flowing through a ground wire is:

$$I_{gw} = -\frac{Z_{pg}(I_a + I_b + I_c)}{Z_g} \quad (13)$$

Using (13) it is possible to reduce the matrix from (5), and form a matrix relationship that consists only of variables and impedances relating to the phase conductors:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} Z_p^g & Z_{pp}^g & Z_{pp}^g \\ Z_{pp}^g & Z_p^g & Z_{pp}^g \\ Z_{pp}^g & Z_{pp}^g & Z_p^g \end{bmatrix} \times \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (14)$$

where the elements of this reduced matrix are as follows:

$$Z_p^g = Z_p - \frac{Z_{pg}^2}{Z_g} \quad (15)$$

$$Z_{pp}^g = Z_{pp} - \frac{Z_{pg}^2}{Z_g} \quad (16)$$

By inserting the matrix relationship (14) into (4), the reduced impedance matrix in symmetric components domain becomes:

$$[Z_{dto}] = \begin{bmatrix} Z_p^g - Z_{pp}^g & 0 & 0 \\ 0 & Z_p^g - Z_{pp}^g & 0 \\ 0 & 0 & Z_f^g + 2Z_{pp}^g \end{bmatrix} \quad (17)$$

The longitudinal impedances for positive Z_d^g , negative Z_i^g and zero phase sequences Z_0^g , are the main diagonal elements of the reduced impedance matrix, obtained as:

$$Z_d^g = Z_i^g = Z_p - Z_{pp} = R_p + j\omega \frac{\mu_0}{2\pi} \ln \frac{D}{r_{pe}} \quad (18)$$

$$Z_0^g = Z_p + 2Z_{pp} - 3 \frac{Z_{pg}^2}{Z_g} \quad (19)$$

by the means of (15), (16) and (17). If the influence of ground wires is not considered, the longitudinal impedances from (18) and (19) are:

$$Z_d = Z_i = Z_p - Z_{pp} = R_p + j\omega \frac{\mu_0}{2\pi} \ln \frac{D}{r_{pe}} \quad (20)$$

$$Z_0 = Z_p + 2Z_{pp} \quad (21)$$

Based on the real and imaginary parts of the complex impedance (21), zero-sequence resistance and zero sequence reactance of an OPL without ground wires are:

$$R_0 = R_p + 3R_g \quad (22)$$

$$X_0 = \omega(L_p + 2M_{pp}) = \omega \frac{\mu_0}{2\pi} \ln \frac{D_{ekv}^3}{r_{pe} D^2} \quad (23)$$

Based on the relationship (19), zero-sequence resistance and zero-sequence reactance of an OPL with one ground wire, taking (22) and (23) into consideration, are expressed as:

$$R_0^g = R_0 - 3 \frac{(R_g^2 - \omega^2 M_{pg}^2)(R_{gw} + R_g) + 2R_g \omega^2 L_g M_{pg}}{(\omega L_g)^2 + (R_{gw} + R_g)^2} \quad (24)$$

$$X_0^g = X_0 - 3 \frac{2(R_g + R_{gw})R_g \omega M_{pg} - (R_g^2 - \omega^2 M_{pg}^2)\omega L_g}{(\omega L_g)^2 + (R_{gw} + R_g)^2} \quad (25)$$

In the case of OPL with two ground wires, the procedure for obtaining the longitudinal electric parameters is the same, but with insertions of one additional row and one additional column in matrix equation (5), i.e.

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} Z_p & Z_{pp} & Z_{pp} & Z_{pg} & Z_{pg} \\ Z_{pp} & Z_p & Z_{pp} & Z_{pg} & Z_{pg} \\ Z_{pp} & Z_{pp} & Z_p & Z_{pg} & Z_{pg} \\ Z_{pg} & Z_{pg} & Z_{pg} & Z_g & Z_{gg} \\ Z_{pg} & Z_{pg} & Z_{pg} & Z_{gg} & Z_g \end{bmatrix} \times \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_{gw} \\ I_{gw} \end{bmatrix} \quad (26)$$

This relationship, in the same manner as (5), takes into account the symmetrical arrangement of the phase conductors and ground wires. The voltages of ground wires are again equal to zero because of their grounding, while the currents are the same due to the symmetrical arrangement. The elements of the impedance matrix from (26) are the same as those in the impedance matrix from (5), and they can be obtained using (6)-(9), while the newly-introduced element, the so-called mutual impedance between the ground wires Z_{gg} , is determined as:

$$Z_{gg} = R_g + j\omega M_{gg} = R_g + j\omega \frac{\mu_0}{2\pi} \ln \frac{D_{ekv}}{D_{gg}} \quad (27)$$

where M_{gg} is mutual inductance, and D_{gg} is the distance between the ground wires.

In this case, the current flowing through one ground wire is:

$$I_{gw} = -\frac{Z_{pg}(I_a + I_b + I_c)}{Z_g + Z_{gg}} \quad (28)$$

Now, the elements of the reduced impedance matrix in the phase domain can be found as:

$$Z_p^{gg} = Z_p - 2 \frac{Z_{pg}^2}{Z_g + Z_{gg}} \quad (29)$$

$$Z_{pp}^{gg} = Z_{pp} - 2 \frac{Z_{pg}^2}{Z_g + Z_{gg}} \quad (30)$$

The reduced impedance matrix in the symmetric component domain, which is obtained in this particular case, has the same form as the matrix in (17). Based on this fact and using the relationships (29) and (30), the longitudinal impedances for the positive, negative, and zero phase sequences of the OPL with two ground wires are:

$$Z_d^{gg} = Z_i^{gg} = Z_p - Z_{pp} = R_p + j\omega \frac{\mu_0}{2\pi} \ln \frac{D}{r_{pe}} \quad (31)$$

$$Z_0^{gg} = Z_p + 2Z_{pp} - 6 \frac{Z_{pg}^2}{Z_g + Z_{gg}} \quad (32)$$

Based on (32), zero-sequence resistance and zero-sequence reactance of the OPL with two ground wires, taking (22) and (23) into consideration, are:

$$R_0^{gg} = R_0 - 6 \frac{(R_g^2 - \omega^2 M_{pg}^2)(R_{gw} + 2R_g) + 2R_g \omega^2 M_{pg}(L_g + M_{gg})}{(\omega L_g + \omega M_{gg})^2 + (2R_g + R_{gw})^2} \quad (33)$$

$$X_0^{gg} = X_0 - 6 \frac{2R_g \omega M_{pg}(2R_g + R_{gw}) - (R_g^2 - \omega^2 M_{pg}^2)\omega(L_g + M_{gg})}{(\omega L_g + \omega M_{gg})^2 + (2R_g + R_{gw})^2} \quad (34)$$

RESULTS AND DISCUSSION

This section presents the obtained results together with their discussions. The results are tabulated for the longitudinal positive, negative and zero sequence impedances of the OPLs with one and two ground wires (Tables I and II). The two tables also contain the ground wire currents obtained for the zero sequence currents of 1 per unit (p.u.) flowing through the phase conductors. The tabulated results include and compare four different cases. In Case 1, the influence of ground wires is ignored, in Case 2, all resistances are neglected, in Case 3, only ground wire resistance is neglected, and in Case 4, in the most accurate case, all the parameters are taken into account. The results are generated for the cases of typical pole constructions of the 110 kV and 400 kV OPLs, which exist in Serbia.

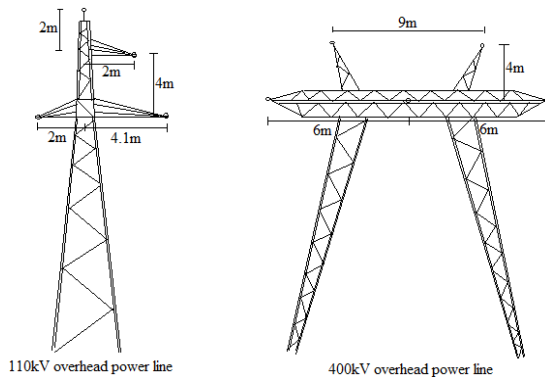


Figure 1. 110 kV and 400 kV OPLs

Fig. 1 shows schematic representations of the 110 kV and 400 kV OPLs, with all the dimensions used in the calculation. As can be seen from Figure 1, the 110 kV OPL is equipped with one ground wire, and the 400 kV OPL is equipped with two ground wires. An Al-Fe conductor with a diameter of 16mm and a resistance of 0.2992 Ω/km is used for the ground wires of both OPLs. The phase conductors of the 110 kV OPL are made of Al-Fe conductors having a diameter of 19 mm and resistance of 0.1572 Ω/km , while the phase conductor of the 400 kV OPL is made of Al-Fe conductors having a diameter of 26.6 mm and resistance of 0.0802 Ω/km . The values of 100 Ωm and 50 Hz are used for the soil

resistivity and the power system frequency, respectively. In addition, the 400 kV OPL has two conductors per phase with an interaxial spacing of 0,4 m. This was the main reason to use the equivalent radius of bundled phase conductors (10) for the calculation in the case of 400 kV OPL. Table 1 outlines the results (longitudinal impedances and ground wire currents) obtained for the 110 kV OPL with one ground wire.

Table 1. Longitudinal impedances and ground wire currents of the 110 kV OPL with one ground wire

Case	$Z_d^{gg}(\Omega/\text{km})$	$Z_i^{gg}(\Omega/\text{km})$	$Z_0^{gg}(\Omega/\text{km})$	$I_{gw}(\text{p. u.})$
1	0.157+j0.405	0.157+j0.405	0.305+j1.376	0
2	0+j0.405	0+j0.405	0+j0.943	-1.323
3	0.157+j0.405	0.157+j0.405	0.203+j0.946	-1.33+j0.11
4	0.157+j0.405	0.157+j0.405	0.361+j0.979	-1.16-j0.35

The results (longitudinal impedances and ground wire currents) obtained for the 400 kV OPL with two ground wires are outlined in Table 2.

Table 2. Longitudinal impedances and ground wire currents of the 400 kV OPL with two ground wires

Case	$Z_d^{gg}(\Omega/\text{km})$	$Z_i^{gg}(\Omega/\text{km})$	$Z_0^{gg}(\Omega/\text{km})$	$I_{gw}(\text{p. u.})$
1	0.08+j0.295	0.08+j0.295	0.228+j1.202	0
2	0+j0.295	0+j0.295	0+j0.642	-0.901
3	0.08+j0.295	0.08+j0.295	0.104+j0.644	-0.91+j0.06
4	0.08+j0.295	0.08+j0.295	0.256+j0.667	-0.83-j0.18

Tables 1 and 2 confirmed that the longitudinal positive and negative sequence impedances of the OPLs are always equal regardless of whether the influence of ground wires are taken into account or not (18), (20) and (31). This can be explained by the fact that OPLs are static components of the power systems, and they have the same impedance for every symmetrical arrangement of the phase conductors and ground wires (as considered in this paper), in which the sum of all phase currents is equal to zero. Independence of longitudinal impedances of the OPLs for positive and negative sequence (sum of all phase currents is equal to zero) from the ground wires is evident considering the expressions for ground wire currents (13) and (28).

Unlike the positive and negative sequences, based on (19), (23) and (32), ground wires have an influence on OPL longitudinal zero sequence impedance. Comparing the results in Tables 1 and 2 for case 1 and case 4, it can be concluded that ground wires slightly increase zero-sequence resistance and in a greater extent reduce zero-sequence reactance of the OPL. Also, by comparing the results from case 3 with those in case 4, for both tables, it can be seen that neglectation of the ground wires resistance, does not have much effect on zero-sequence reactance, but leads to a big decrease in zero-sequence resistance value, for both OPL. Considering results from cases 2 and 4 it can be concluded that, besides the calculation simplification and the loss of resistance information, neglectation of all resistances only slightly reduces the zero-sequence reactance of the OPLs. This change in zero-sequence impedance of OPLs which ground wires create mainly affects the protection system

of OPL, which operation is based on the proper determination of fault loop impedance.

Based on Tables 1 and 2, it can be observed that the ground wire current is approximately in counter-phase with zero-sequence currents in phase conductors which have 1 p.u. value. The ground wire resistance slightly reduces the intensity and increases the phase angle of the ground wire current. Moreover, a higher intensity of the ground wire current is obtained for the 110 kV OPL, due to the smaller interaxial spacings between the phase conductors and the ground wire and the fact that the 110 kV power line has only one ground wire.

CONCLUSION

In this paper, the influence of ground wires on the longitudinal resistance and reactance of OPLs was successfully quantified. It was shown that, regardless of the number of ground wires, in the case of symmetrically arranged conductors of OPLs or the case of achieved transposition, the ground wires do not affect the longitudinal positive and negative sequence impedances. In addition, it was found that the influence only exists for the longitudinal zero sequence impedance of OPLs, so that the corresponding resistance slightly increases, while the corresponding reactance decreases. Moreover, it was shown that ignoring the resistance of the ground wires significantly reduces the zero-sequence resistance of the OPLs. In the end, based on the obtained results, it can be concluded that in asymmetric operating conditions in which zero sequence currents appear, ground wires change the values of resistance and reactance of OPLs, which must be considered especially when designing their protection system.

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BIOGRAPHY of the first author

Nikola N. Krstić was born in 1995. in Niš, Serbia. He graduated in 2018. and completed his master's academic studies in 2019. at the Faculty of Electronic Engineering, University of Niš.

His main areas of research include power system analysis, optimization and renewable energy sources. He is currently working as a Teaching Assistant at the Faculty of Electronic Engineering, University of Niš.



UTICAJ ZAŠTITNIH UŽADI NA AKTIVNU OTPORNOST I REAKTANSU VISOKONAPONSKIH NADZEMNIH VODOVA

Nikola Krstić, Dragan Tasić, Dardan Klimenta

Rezime: U ovom radu je razmatran uticaj zaštitnih užadi na aktivnu otpornost i reaktansu (podužnu impedansu) visokonaponskih nadzemnih vodova (OPLs) i detaljno opisana metoda za njegovo izračunavanje. Ovo je važno pri određivanju tokova snaga i projektovanju zaštitnog sistema nadzemnih vodova, posebno onih koji koriste distantne releje. Pored simetričnih razmatrana su i nesimetrična radna stanja nadzemnih vodova, za čiju analizu je korišćen metod simetričnih komponenti. Ovde se konkretno misli na određivanje podužne impedanse nadzemnog voda za direktni, inverzni i nulti redosled, u svakom razmatranom slučaju. Posebna pažnja je posvećena simetričnom sistemu nultog redosleda, jer je uticaj zaštitnih užadi na promenu podužne impedanse nadzemnog voda najveći u tom slučaju. Obradeni su slučajevi nadzemnih vodova sa jednim (110 kV vod) i dva zaštitna užeta (400 kV vod), koristeći stvarne vrednosti njihovih parametara. Vrednosti podužnih impedansi nadzemnih vodova, dobijene sa i bez uvažavanja zaštitnih užadi ili nekih od njihovih parametara, su međusobno upoređene, na osnovu čega su izvedeni odgovarajući zaključci.

Ključne reči: zaštitno uže, nadzemni vod, simetrične komponente, podužna impedansa.