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O. Bialobrzheskyi[*1],
orcid.org/0000-0003-1669-4580,
O. Todorov[1],
orcid.org/0000-0001-5703-6790,
A. Postil[1],
orcid.org/0000-0001-9411-7047,
M. Bezzub[1],
orcid.org/0000-0002-5595-4464,
A. Sulym[2],
orcid.org/0000-0001-8144-8971

1 – Kremenchuk Mykhailo Ostrohradskyi National University, Kremenchuk, Ukraine
2 – State Enterprise "Ukrainian Scientific Railway Car Building Research Institute", Kremenchuk, Ukraine
[*] Corresponding author e-mail: seemal@kdu.edu.ua

CABLE LINE EQUIVALENT CIRCUIT PARAMETERS DETERMINATION USING THE INSTANTANEOUS POWER COMPONENTS

Purpose. Development of a method for determining the cable line substitution scheme parameters based on the components of its instantaneous power.

Methodology. Determination of unknown parameters of the cable line mode using the harmonic balance method. Determination of the U-shaped substitution scheme elements parameters is performed using power harmonics and their balance at the corresponding frequencies. For frequency-dependent elements, it is taken into account that the same power harmonic can be formed by different current and voltage harmonics.

Findings. A method for determining the parameters of the cable line substitution scheme using the power components of its elements is proposed, which is distinguished by the fact that the total number of system equations for determining the parameters can be increased due to the use of power. The study of the proposed method for determining the cable line substitution scheme parameters based on the power components, based on the model compiled in the visual programming package, allowed us to establish that the largest parameter determination error is characteristic of active conduction.

Originality. With the instantaneous power determination of the cable line substitution scheme reactive elements, it was found that during the calculation of the instantaneous power there is a peculiarity of taking into account the voltage harmonic number depending on the combination of harmonic numbers.

Practical value. The proposed method can be developed on the sectioning of the U-shaped line substitution scheme to determine the change in the cable line substitution scheme parameters during its operation without disconnecting the line, unlike existing methods.

Keywords: *cable line, power, voltage, harmonics, orthogonal components, harmonic frequency*

Introduction. Cable lines are the main element for transporting electricity. Monitoring the technical condition of cable lines is a very important process, as a line failure will cause a power outage, and in large enterprises, this will lead to a shutdown of technical equipment, which in turn will cause significant economic losses. Monitoring the technical condition of a cable line in an enterprise can be quite difficult or impossible due to the lack of physical access to the line or its section.

To monitor the condition of a cable line, methods are usually used where the line is disconnected from the network, such as the travelling wave method, where a pulse is launched into the line, and the reflected wave, by its shape and time of receipt, indicates the type of damage and approximate location [1]. However, this solution is sometimes impossible due to certain reasons. Therefore, to prevent complex damage, it is rational to monitor the condition of the line by changing the parameters of its replacement scheme during operation.

This method allows you to monitor the cable line technical condition and work in tandem with the protection system to ensure timely operation of the latter.

Given that visual inspection or diagnostics of most cable lines requires significant preparatory and dismantling work, this issue is relevant.

Literature review. The study of the state of insulation of high-voltage cable lines by monitoring dielectric losses at the cross-insulation connection was carried out in [2, 3]. Data are collected using current sensors installed in grounding boxes. The calculation is based on the study of impedance changes in different parts of the cable line. The disadvantage of this solution is that it can be used only for high-voltage networks and additional structures must be introduced to use it.

In [4, 5], the state of insulation is analysed by observing the manifestation of partial discharges. The work is based on the principle that a direct current is applied to the line and the change in the electric field in the insulation is observed. However, during transient processes, the data obtained may differ from the AC electric field. The study is performed using diagnostics in an automatic uncontrolled manner based on an algorithm for separating noise from partial discharges.

An operational method for assessing the relative dielectric losses in cross-linked polyethylene high-voltage cables with cross-coupling was developed by the authors in [6]. This method uses data from industrial frequency leakage current sensors. To improve the measurement in the mode without disconnecting the cable line, an error analysis was carried out, including the characteristics of current sensors, data acquisition accuracy, synchronisation error, and system frequency fluctuations. The calculations are based on the actual value measurement of the leakage current in the relevant areas.

There are also works in which the authors investigate the state of the cable line using replacement schemes. For example, in [7], based on the model of a power line with distributed parameters at a line length of 500 km, the number of segments sufficient to obtain voltages and currents with high accuracy was analysed.

The study of a line with distributed parameters was also carried out in [8]. The analysis is carried out by comparing the frequency characteristics of the replacement circuits with distributed parameters with different numbers of segments. This is used to limit the dimensionality of the line cascade to the number of segments at which the error will have a negligible effect on accuracy.

Determination of cable line damage was performed in [9]. The algorithm for determining the damage to the line is performed by determining the change in the voltage of the forward and reverse sequences along the line. However, it should be noted that this method can give a false result in conditions of non-sinusoidal voltage, which is a significant drawback.

A method that uses a system of equations of complex variables in the A-form to determine the parameters of a transmission line is described in [10, 11]. A similar approach is used in [12], which investigates the method of fault localisation in one-way direct power supply systems for electric traction. Based on a model of distributed transmission line parameters, the authors determine the position of the short circuit using the measured current and voltage values at the ends of the traction line under study. Additionally, the authors investigate the effect of transient resistance and locomotive position on fault location. These methods are quite simple as they do not require the use of complex integral operations, but the use of such methods in conditions of non-sinusoidal current and/or voltage is impossible.

In [13, 14], a model of a three-phase cable is presented for modelling transients in power supply systems. The model is based on concentrated parameters and is represented by cascaded π-sections. The modal transformation method is used in the proposed model. The frequency-dependent elements of the corresponding modal transformation matrices were equipped with rational functions. The calculation of the corresponding modal transformation matrices was implemented using the Levenberg-Marquardt algorithm. As a result, the parameters of the cable transmission line circuits were reduced by the authors to the well-known u-shaped substitution scheme.

Thus, the problem of determining the parameters of the cable transmission line replacement scheme has certain solutions, but is still relevant, especially in conditions of non-sinusoidal current and/or voltage.

The purpose of the work. Development of a method for determining the parameters of a cable line replacement scheme by its instantaneous power components.

Main material and research results. Depending on the type of transmission line, different replacement schemes are used. In some cases, when the wavelength is proportional to the length of the line, line schemes with distributed parameters are used, in other cases – with concentrated parameters. In the latter case, the most complete substitution scheme, which takes into account the active resistance, inductance of the wire, and insulation properties, is the U-shaped substitution scheme (Fig. 1). It has a structure that corresponds to the physical processes for lines of relatively short length and allows for mode calculation. However, even such a substitution scheme is difficult from the point of view of the inverse problem – determining the scheme parameters from known mode parameters. Given the known input and output currents and voltages, the presence of an *RL* section in a U-shaped replacement circuit complicates the task due to the unknown voltage distribution in the section.

To determine the parameters of the substitution circuit, we will use a method based on the instantaneous power balance [15] under the condition of non-sinusoidal and periodic currents and voltages. To do this, write the power equation of the circuit

$$\begin{cases} p = p_1 - p_2 \\ p = p_G + p_C + p_R + p_L \end{cases}, \qquad (1)$$

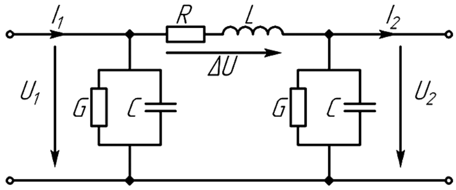

Fig. 1. U-shaped substitution scheme

where p_1 is power at the input of the replacement circuit; p_2 – power at the output of the replacement circuit; $p_G = p_{G1} + p_{G2}$ – the sum of powers at the input and output conductive elements; $p_C = p_{C1} + p_{C2}$ – the capacities sum at the input and output elements of the tank; p_R – power of the active resistance element; p_L – inductor element power, which in general are determined as follows.

In accordance with the accepted method [16], the determination of the U-shaped substitution scheme elements parameters is performed using power harmonics and their balance at the corresponding frequencies. In the trigonometric form, power harmonics are reflected in two forms of recording that are identical: using the amplitude and harmonic phase; using orthogonal harmonic components. In other words, an arbitrary power harmonic of an element can be represented as follows

$$\begin{aligned} p_s &= P_s \cos(s\omega t - \psi_s) = \\ &= P_s \cos(\psi_s)\cos(s\omega t) + P_s \sin(\psi_s)\sin(s\omega t) = \\ &= P_{a.s}\cos(s\omega t) + P_{b.s}\sin(s\omega t), \end{aligned}$$

where P_s is harmonic amplitude; s – harmonic frequency; ω – angular frequency; t – time; ψ_s – phase shift; $P_{a.s}$ – harmonic amplitude cosine component; $P_{b.s}$ – harmonic amplitude sine component.

With known harmonics ($k \in K$) voltage and harmonics ($n \in N$) current, the power caused by them will take the form

$$\begin{aligned} p_{k,n} &= U_k \cdot \sin(k\omega t + \varphi_{u.k}) \cdot I_n \cdot \sin(n\omega t + \varphi_{i.n}) = \\ &= 0.5 \cdot \cos\big((k-n)\omega t\big) \cdot \big(U_{k.a} \cdot I_{n.a} + U_{k.b} \cdot I_{n.b}\big) + \\ &+ 0.5 \cdot \cos\big((k+n)\omega t\big) \cdot \big(U_{k.b} \cdot I_{n.b} - U_{k.a} \cdot I_{n.a}\big) + \\ &+ 0.5 \cdot \sin\big((k-n)\omega t\big) \cdot \big(U_{k.a} \cdot I_{n.b} - U_{k.b} \cdot I_{n.a}\big) + \\ &+ 0.5 \cdot \sin\big((k+n)\omega t\big) \cdot \big(U_{k.a} \cdot I_{n.b} + U_{k.b} \cdot I_{n.a}\big), \end{aligned} \qquad (2)$$

where k is voltage harmonic number; n – current harmonic number; $\varphi_{u.k}$ – k^{th} harmonic voltage phase shift; $\varphi_{i.n}$ – n^{th} harmonic current phase shift; U_k – voltage harmonic amplitude; I_n – current harmonic amplitude; $U_{k.a}$ – voltage harmonic cosine component amplitude; $I_{n.a}$ – current harmonic cosine component amplitude; $U_{k.b}$ – voltage harmonic sine component amplitude; $I_{n.b}$ – current harmonic sine component amplitude.

Given that the current and voltage at the input and output of the circuit are known, and the voltages in the circuit branches are known, the currents in the circuit branches are unknown. Determination of power $p_{G1}(t)$, $p_{G2}(t)$ is straightforward and can be performed using the appropriate voltages and element parameters. Accordingly, the current and voltage harmonics on the conductor are related as follows

$$i_G = u \cdot G = U_h \cdot \sin(h\omega t + \varphi_{u.h}) \cdot G, \qquad (3)$$

where h is harmonic value; G – substitution circuit element active conductivity.

Current and voltage at the capacitor

$$i_C = C \cdot \frac{du}{dt} = \sum_h U_h \cdot \cos(h\omega t + \varphi_{u.h}) \cdot B_C, \qquad (4)$$

where $B_C = Ch\omega$ – capacitive conductivity of the substitution circuit element.

In the case under consideration, the active resistance R and the inductance L are related quantities since their common voltage can be determined $\Delta u(t) = u_1(t) - u_2(t)$ whose arbitrary harmonic is equal to

$$\begin{aligned} \Delta U_h \cdot \sin(h\omega t + \varphi_{\Delta u.h}) &= I_{RL.h} \cdot \sin(h\omega t + \varphi_{i.RL.h}) \cdot R + \\ &+ I_{RL.h} \cdot \cos(h\omega t + \varphi_{i.RL.h}) \cdot L \cdot h\omega, \end{aligned} \qquad (5)$$

where ΔU_h is the voltage amplitude on the RL elements of the h^{th} harmonic; $I_{RL.h}$ is the current amplitude on the RL elements of the h^{th} harmonic; $\varphi_{\Delta u.h}$ – voltage h^{th} harmonic phase; $\varphi_{i.RL.h}$ – the h^{th} current harmonic phase. Based on this approach, we will immediately consider the power p_R and p_L through their total value $p_{RL} = p_R + p_L$.

Based on (5), the relationship between the h^{th} current harmonic orthogonal components and the h^{th} voltage harmonic orthogonal components for the RL section can be expressed as follows

$$\begin{gathered}\Delta U_{a.h}\cdot\sin(h\omega t)+\Delta U_{b.h}\cdot\cos(h\omega t)=\\=(I_{RL.a.h}\cdot\sin(h\omega t)+I_{RL.b.h}\cdot\cos(h\omega t))\cdot R+\\+(I_{RL.a.h}\cdot\cos(h\omega t)-I_{RL.b.h}\cdot\sin(h\omega t))\cdot L\cdot h\omega,\end{gathered}\tag{6}$$

where $U_{a.h} = \Delta U_h \cdot \cos(\varphi_{\Delta u.h})$ is sinusoidal orthogonal voltage component amplitude; $\Delta U_{a.h} = \Delta U_h \cdot \sin(\varphi_{\Delta u.h})$ – cosine orthogonal voltage component amplitude; $I_{RL.a.h} = I_{RL.h} \times \times \cos(\varphi_{\Delta u.h})$ – sinusoidal orthogonal current component amplitude; $I_{RL.b.h} = I_{RL.h} \cdot \sin(\varphi_{\Delta u.h})$ – cosine orthogonal current component amplitude.

Performing simple transformations, grouping of sine and cosine components, and simplifications, we obtain a matrix form of the relationship between current and voltage amplitudes through parameters for the RL section

$$\begin{pmatrix}I_{RL.h.a}\\I_{RL.h.b}\end{pmatrix}=\begin{pmatrix}R & L\cdot h\omega\\-L\cdot h\omega & R\end{pmatrix}^{-}\cdot\begin{pmatrix}\Delta U_{h.a}\\\Delta U_{h.b}\end{pmatrix}.\tag{7}$$

Then the currents in (2) for the RL elements of the section will take the form

$$\begin{cases}I_{RL.h.a}=\dfrac{R\cdot\Delta U_{h.a}-L\cdot h\omega\cdot\Delta U_{h.b}}{R^2+(L\cdot h\omega)^2}\\I_{RL.h.b}=\dfrac{R\cdot\Delta U_{h.b}+L\cdot h\omega\cdot\Delta U_{h.a}}{R^2+(L\cdot h\omega)^2}\end{cases}.\tag{8}$$

After completing the transformation link, we will enter the following components as active G_R and reactive B_L conductivity of the RL section for an arbitrary harmonic

$$\begin{cases}G_R=\dfrac{R}{R^2+(L\cdot h\omega)^2}\\B_L=\dfrac{L\cdot h\omega}{R^2+(L\cdot h\omega)^2}\end{cases}.\tag{9}$$

Using the power balance in the circuit of (1) as

$$\begin{gathered}p_1-p_2=p_{G1}+p_{G2}+p_{C1}+p_{C2}+p_{RL}=u_1^2(t)G_1+u_2^2(t)G_2+\\+u_1(t)\frac{du_1(t)}{dt}C_1+u_2(t)\frac{du_2(t)}{dt}C_2+\Delta u(t)i_{RL}(t).\end{gathered}\tag{10}$$

Let us write down the power of each of the circuit elements (Fig. 1), taking into account the method described in [17, 18], separating the current and voltage harmonics, as follows:

- power at the input of the circuit

$$\begin{aligned}p_1=\frac{1}{2}\cdot\sum_k\sum_n\Big[\big(&\cos((k-n)\omega t)(U_{1.a.k}I_{1.a.n}+U_{1.b.k}I_{1.b.n})+\\&+\cos((k+n)\omega t)(U_{1.b.k}I_{1.b.n}-U_{1.a.k}I_{1.a.n})+\\&+\sin((k-n)\omega t)(U_{1.a.k}I_{1.b.n}-U_{1.b.k}I_{1.a.n})+\\&+\sin((k+n)\omega t)(U_{1.a.k}I_{1.b.n}+U_{1.b.k}I_{1.a.n})\Big],\end{aligned}\tag{11}$$

where k is voltage harmonic number; n – current harmonic number; $U_{1.a.k}$ – input voltage k-harmonic cosine component of the; $U_{1.b.k}$ – input voltage k-harmonic sine component; $I_{1.a.n}$ – input current n-harmonic cosine component; $I_{1.b.n}$ – input current n-harmonic sine component;

- power at the output of the circuit

$$\begin{aligned}p_2=\frac{1}{2}\sum_k\sum_n\Big[&\cos((k-n)\omega t)(U_{2.a.k}I_{2.a.n}+U_{2.b.k}I_{2.b.n})+\\&+\cos((k+n)\omega t)(U_{2.b.k}I_{2.b.n}-U_{2.a.k}I_{2.a.n})+\\&+\sin((k-n)\omega t)(U_{2.a.k}I_{2.b.n}-U_{2.b.k}I_{2.a.n})+\\&+\sin((k+n)\omega t)(U_{2.a.k}I_{2.b.n}+U_{2.b.k}I_{2.a.n})\Big],\end{aligned}\tag{12}$$

where $U_{2.a.k}$ is output voltage k-harmonic cosine component; $U_{2.b.k}$ – output voltage k-harmonic sine component; $I_{2.a.n}$ – output current n-harmonic cosine component; $I_{2.b.n}$ – output current n-harmonic sine component;

- active conductivity power at the beginning and end of the line

$$\begin{aligned}p_{G1}=\frac{1}{2}\sum_k\sum_n\Big[&\cos((k-n)\omega t)(U_{1.a.k}U_{1.a.n}+U_{1.b.k}U_{1.b.n})+\\&+\cos((k+n)\omega t)(U_{1.b.k}U_{1.b.n}-U_{1.a.k}U_{1.a.n})+\\&+\sin((k-n)\omega t)(U_{1.a.k}U_{1.b.n}-U_{1.b.k}U_{1.a.n})+\\&+\sin((k+n)\omega t)(U_{1.a.k}U_{1.b.n}+U_{1.b.k}U_{1.a.n})\Big]G_1;\end{aligned}\tag{13}$$

$$\begin{aligned}p_{G2}=\frac{1}{2}\sum_k\sum_n\Big[&\cos\big((k-n)\omega t\big)\big(U_{2.a.k}U_{2.a.n}+U_{2.b.k}U_{2.b.n}\big)+\\&+\cos\big((k+n)\omega t\big)\big(U_{2.b.k}U_{2.b.n}-U_{2.a.k}U_{2.a.n}\big)+\\&+\sin\big((k-n)\omega t\big)\big(U_{2.a.k}U_{2.b.n}-U_{2.b.k}U_{2.a.n}\big)+\\&+\sin\big((k+n)\omega t\big)\big(U_{2.a.k}U_{2.b.n}+U_{2.b.k}U_{2.a.n}\big)\Big]G_2;\end{aligned}\tag{14}$$

- is capacitor power at the beginning and end of the line

$$\begin{aligned}p_{C1}=\frac{1}{2}\sum_k\sum_n\Big[&\cos((k-n)\omega t)(U_{1.b.k}U_{1.a.n}-U_{1.a.k}U_{1.b.n})+\\&+\cos((k+n)\omega t)(U_{1.a.k}U_{1.b.n}+U_{1.b.k}U_{1.a.n})+\\&+\sin((k-n)\omega t)(U_{1.a.k}U_{1.a.n}-U_{1.b.k}U_{1.b.n})+\\&+\sin((k+n)\omega t)(U_{1.a.k}U_{1.a.n}+U_{1.b.k}U_{1.b.n})\Big]C_1n\omega;\end{aligned}\tag{15}$$

$$\begin{aligned}p_{C2}=\frac{1}{2}\sum_k\sum_n\Big[&\cos((k-n)\omega t)(U_{2.b.k}U_{2.a.n}-U_{2.a.k}U_{2.b.n})+\\&+\cos((k+n)\omega t)(U_{2.a.k}U_{2.b.n}+U_{2.b.k}U_{2.a.n})+\\&+\sin((k-n)\omega t)(U_{2.a.k}U_{2.a.n}-U_{2.b.k}U_{2.b.n})+\\&+\sin((k+n)\omega t)(U_{2.a.k}U_{2.a.n}+U_{2.b.k}U_{2.b.n})\Big]C_2n\omega;\end{aligned}\tag{16}$$

- is the RL site power, taking into account (6 and 8)

$$\begin{aligned}p_{RL}=\frac{1}{2}\sum_k\sum_n\Big[&\cos((k-n)\omega t)(\Delta U_{a.k}\Delta U_{a.n}+\Delta U_{b.k}\Delta U_{b.n})G_R+\\&+\cos((k-n)\omega t)(\Delta U_{b.k}\Delta U_{a.n}-\Delta U_{a.k}\Delta U_{b.n})B_L+\\&+\cos((k+n)\omega t)(\Delta U_{b.k}\Delta U_{b.n}-\Delta U_{a.k}\Delta U_{b.n})G_R+\\&+\cos((k+n)\omega t)(\Delta U_{a.k}\Delta U_{b.n}+\Delta U_{b.k}\Delta U_{a.n})B_L+\\&+\sin((k-n)\omega t)(\Delta U_{a.k}\Delta U_{b.n}-\Delta U_{b.n}\Delta U_{a.n})G_R+\\&+\sin((k-n)\omega t)(\Delta U_{a.k}\Delta U_{a.n}-\Delta U_{b.k}\Delta U_{b.n})B_L+\\&+\sin((k+n)\omega t)(\Delta U_{a.k}\Delta U_{b.n}+\Delta U_{b.k}\Delta U_{a.n})G_R+\\&+\sin((k+n)\omega t)(\Delta U_{a.k}\Delta U_{a.n}+\Delta U_{b.k}\Delta U_{b.n})B_L\Big].\end{aligned}\tag{17}$$

Power balance is performed for each power harmonic orthogonal component $s = (k \pm n)$ on each circuit element. Let us take two sections G_1C_1 and G_2C_2 for equivalent to the elements $G_1 = G_2 = G$ and $C_1 = C_2 = C$.

$$\begin{gathered}p_G=p_{G1}+p_{G2}=(u_1(t)^2+u_2(t)^2)G;\\p_C=p_{C1}+p_{C2}=\left(u_1\frac{du_1}{dt}+u_2\frac{du_2}{dt}\right)C.\end{gathered}\tag{18}$$

As a result, it is possible to draw up a system of equations with a total number of $S = K + N$ by the corresponding power harmonics s

$$\begin{cases} p_{1.0}-p_{2.0}=p_{G.0}+p_{C.0}+p_{GR.0}+p_{BL.0} \\ p_{1.1}-p_{2.1}=p_{G.1}+p_{C.1}+p_{GR.1}+p_{BL.1} \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ p_{1.s}-p_{2.s}=p_{G.s}+p_{C.s}+p_{GR.s}+p_{BL.s} \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ p_{1.S}-p_{2.S}=p_{G.S}+p_{C.S}+p_{GR.S}+p_{BL.S} \end{cases}. \tag{19}$$

Grouping powers accordingly and reducing trigonometric functions $\sin(k\pm n)\omega t=\sin(s\omega t)$ and $\cos(k\pm n)\omega t=\cos(s\omega t)$, it becomes possible to write a system of equations for the circuit elements orthogonal power components amplitudes of the for the corresponding power frequencies s

$$\begin{cases} P_{1.a.0}-P_{2.a.0}=P_{G.a.0}+P_{C.a.0}+P_{GR.a.0}+P_{BL.a.0} \\ P_{1.b.0}-P_{2.b.0}=P_{G.b.0}+P_{C.b.0}+P_{GR.b.0}+P_{BL.b.0} \\ P_{1.a.1}-P_{2.a.1}=P_{G.a.1}+P_{C.a.1}+P_{GR.a.1}+P_{BL.a.1} \\ P_{1.b.1}-P_{2.b.1}=P_{G.b.1}+P_{C.b.1}+P_{GR.b.1}+P_{BL.b.1} \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ P_{1.a.S}-P_{2.a.S}=P_{G.a.S}+P_{C.a.S}+P_{GR.a.S}+P_{BL.a.S} \\ P_{1.b.S}-P_{2.b.S}=P_{G.b.S}+P_{C.b.S}+P_{GR.b.S}+P_{BL.b.S} \end{cases}. \tag{20}$$

The formation of elements orthogonal power harmonic components of the replacement circuit whose parameters do not depend on frequency does not present any difficulties [19, 20]. At the same time, there is a certain peculiarity for frequency-dependent elements. Let us consider it for the capacitance power. First, it should be borne in mind that the same power harmonic can be formed by different current and voltage harmonics, for example

$$\begin{cases} s=k-n=5-1=4 \\ s=k+n=1+3=4 \end{cases}. \tag{21}$$

At first glance, this combination does not raise any questions. But, if we consider the process of forming capacitor power harmonics, for example C_1

$$\begin{aligned} p_{C1.s}=0.5 &\sum_{\substack{k,n\\ s=(k-n)}}(U_{1.b.k}U_{1.a.n}-U_{1.a.k}U_{1.b.n})\tilde{N}_1 n^{-}\omega\cos(s\omega t)+ \\ +0.5 &\sum_{\substack{k,n\\ s=(k+n)}}(U_{1.a.k}U_{1.b.n}+U_{1.b.k}U_{1.a.n})\tilde{N}_1 n^{+}\omega\cos(s\omega t)+ \\ +0.5 &\sum_{\substack{k,n\\ s=(k-n)}}(U_{1.a.k}U_{1.a.n}-U_{1.b.k}U_{1.b.n})\tilde{N}_1 n^{-}\omega\sin(s\omega t)+ \\ +0.5 &\sum_{\substack{k,n\\ s=(k+n)}}(U_{1.a.k}U_{1.a.n}+U_{1.b.k}U_{1.b.n})\tilde{N}_1 n^{+}\omega\sin(s\omega t), \end{aligned} \tag{22}$$

i. e. for the above example $n^{-}=1$, a $n^{+}=3$. Thus, when forming power amplitudes, it is necessary to take the of the second parameter harmonic value.

Let us assume the voltage and current spectrum to be such that it allows us to form power harmonics 2, 4, 6, which is sufficient to compose six equations according to system (20). Given the large volume, for example, let us write one of them for the cosine orthogonal component of the $s=4$ power harmonic

$$P_{1.a.4}-P_{2.a.4}=P_{G.a.4}+P_{C.a.4}+P_{GR.a.4}+P_{BL.a.4};$$

$$\begin{aligned} P_{1.a.4}-P_{2.a.4}= &\sum_{\substack{k,n\\ (k-n)=4}}(U_{1.a.k}I_{1.a.n}+U_{1.b.k}I_{1.b.n})+ \\ &+\sum_{\substack{k,n\\ (k+n)=4}}(U_{1.b.k}I_{1.b.n}-U_{1.a.k}I_{1.a.n})- \\ &-\sum_{\substack{k,n\\ (k-n)=4}}(U_{2.a.k}I_{2.a.n}+U_{2.b.k}I_{2.b.n})- \\ &-\sum_{\substack{k,n\\ (k+n)=4}}(U_{2.b.k}I_{12b.n}-U_{2.a.k}I_{2.a.n}); \end{aligned}$$

$$\begin{aligned} P_{G.a.4}= &\sum_{\substack{k,n\\ (k-n)=4}}(U_{1.a.k}U_{1.a.n}+U_{1.b.k}U_{1.b.n})G_1+ \\ &+\sum_{\substack{k,n\\ (k+n)=4}}(U_{1.b.k}U_{1.b.n}-U_{1.a.k}U_{1.a.n})G_1+ \\ &+\sum_{\substack{k,n\\ (k-n)=4}}(U_{2.a.k}U_{2.a.n}+U_{2.b.k}U_{2.b.n})G_2+ \\ &+\sum_{\substack{k,n\\ (k+n)=4}}(U_{2.b.k}U_{2.b.n}-U_{2.a.k}U_{2.a.n})G_2; \end{aligned}$$

$$\begin{aligned} P_{C.a.4}= &\sum_{\substack{k,n\\ (k-n)=4}}(U_{1.b.k}U_{1.a.n}-U_{1.a.k}U_{1.b.n})C_1 n\omega+ \\ &+\sum_{\substack{k,n\\ (k+n)=4}}(U_{1.a.k}U_{1.b.n}+U_{1.b.k}U_{1.a.n})C_1 n\omega+ \\ &+\sum_{\substack{k,n\\ (k-n)=4}}(U_{2.b.k}U_{2.a.n}-U_{2.a.k}U_{2.b.n})C_2 n\omega+ \\ &+\sum_{\substack{k,n\\ (k+n)=4}}(U_{2.a.k}U_{2.b.n}+U_{2.b.k}U_{2.a.n})C_2 n\omega; \end{aligned}$$

$$\begin{aligned} P_{GR.a.4}= &\sum_{\substack{k,n\\ (k-n)=4}}\left(\Delta U_{a.k}\Delta U_{a.n}+\Delta U_{b.k}\Delta U_{b.n}\right)G_R+ \\ &+\sum_{\substack{k,n\\ (k+n)=4}}\left(\Delta U_{b.k}\Delta U_{b.n}-\Delta U_{a.k}\Delta U_{b.n}\right)G_R; \end{aligned}$$

$$\begin{aligned} P_{BL.a.4}= &\sum_{\substack{k,n\\ (k-n)=4}}(\Delta U_{b.k}\Delta U_{a.n}-\Delta U_{a.k}\Delta U_{b.n})B_L+ \\ &+\sum_{\substack{k,n\\ (k+n)=4}}(\Delta U_{a.k}\Delta U_{b.n}+\Delta U_{b.k}\Delta U_{a.n})B_L. \end{aligned}$$

Let us simplify the entry form by introducing intermediate notation

$$\begin{aligned} P_{1.a.4}-P_{2.a.4}&=U^2_{G1.a.4}G_1+U^2_{G2.a.4}G_2+ \\ &+U^2_{C1.a.4}C_1+U^2_{C2.a.4}C_2+\Delta U^2_{GR.a4}G_R+\Delta U^2_{BL.a4}B_L. \end{aligned}$$

Then the system of equations (20) can be written in matrix form, taking into account the way the amplitudes of the orthogonal components of power harmonics are formed

$$\mathbf{P}=\mathbf{U}\times\mathbf{Y}, \tag{23}$$

where **Y** is conductivity matrix; **U** – matrix of voltage orthogonal components products; **P** – matrix of circuit orthogonal power components.

Matrix **Y** elements parameters consists of U-shaped substitution scheme, represented through conductivities, and has the form

$$\mathbf{Y}=(G_1 \quad G_2 \quad C_1 \quad C_2 \quad G_R \quad B_L)^T. \tag{24}$$

Matrix **U**

$$\mathbf{U}=\begin{pmatrix} U^2_{G1.a.2} & U^2_{G2.a.2} & U^2_{C1.a.2} & U^2_{C2.a.2} & \Delta U^2_{GR.a2} & \Delta U^2_{BL.a2} \\ U^2_{G1.b.2} & U^2_{G2.b.2} & U^2_{C1.b.2} & U^2_{C2.b.2} & \Delta U^2_{GR.b2} & \Delta U^2_{BL.b2} \\ U^2_{G1.a.4} & U^2_{G2.a.4} & U^2_{C1.a.4} & U^2_{C2.a.4} & \Delta U^2_{GR.a4} & \Delta U^2_{BL.a4} \\ U^2_{G1.b.4} & U^2_{G2.b.4} & U^2_{C1.b.4} & U^2_{C2.b.4} & \Delta U^2_{GR.b4} & \Delta U^2_{BL.b4} \\ U^2_{G1.a.6} & U^2_{G2.a.6} & U^2_{C1.a.6} & U^2_{C2.a.6} & \Delta U^2_{GR.a6} & \Delta U^2_{BL.a6} \\ U^2_{G1.b.6} & U^2_{G2.b.6} & U^2_{C1.b.6} & U^2_{C2.b.6} & \Delta U^2_{GR.b6} & \Delta U^2_{BL.b6} \end{pmatrix}. \tag{25}$$

Matrix **P**

$$\mathbf{P}=\begin{pmatrix} P_{1.a.2}-P_{2.a.2} \\ P_{1.b.2}-P_{2.b.2} \\ P_{1.a.4}-P_{2.a.4} \\ P_{1.b.4}-P_{2.b.4} \\ P_{1.a.6}-P_{2.a.6} \\ P_{1.b.6}-P_{2.b.6} \end{pmatrix}. \tag{26}$$

Thus, the unknown conductivity matrix is determined by

$$\mathbf{Y} = \mathbf{U}^{-1} \times \mathbf{P}. \tag{27}$$

The proposed method will be tested using a model of an electrical installation with a three-phase controlled semiconductor rectifier supplied by a 6 kV cable line. The model was synthesised in a visual programming package (Fig. 3). The semiconductor converter is powered by a three-phase transformer. The transformer is connected to the power source by a cable line (represented by a substitution diagram in accordance with Fig. 1). The current and voltage are monitored at the beginning and end of the cable line. The system is supplied with a voltage of 6 kV and the line length is assumed to be 10 km. Other consumers are not included. The line is made according to the U-shaped substitution scheme with the following parameters: R = 0.346 (Ohm/km); L = 0.109 (mH/km); C = = 0.0696 (μF/km); l = 10 (km); N = 5; G = 0.348 (MOhm /km); a load consisting of a thyristor converter with a load in a DC circuit of RL type, with parameters R = 0.63 (Ohm); L = = 5 (mH).

Time diagrams of current and voltage at the beginning and end of the cable line are shown in Figs. 3 and 4, these diagrams are the initial information used for further calculations. The obvious current distortions caused by the thyristor converter, taking into account the line and system parameters, lead to voltage distortions. Analysing the voltages and currents shown in the figures, the first thing that can be noticed without using additional mathematical operations is a slight drop in voltage and an increase in the steepness of the pulses. As for the currents, the most noticeable thing is the absence of damped oscillations in the output currents.

Fig. 5 shows the changes in voltage and current at the beginning of the line relative to its end. In both cases, these changes are quite complex and are extremely non-sinusoidal.

The graphs clearly show that the voltage difference takes on a form that corresponds more to the alternating current, with the only difference being the appearance of sharp drops at the time of stabilisation. Such changes lead to the conclusion that voltage losses directly depend on the amount of current flowing. At the same time, the current difference has a more pronounced fun-

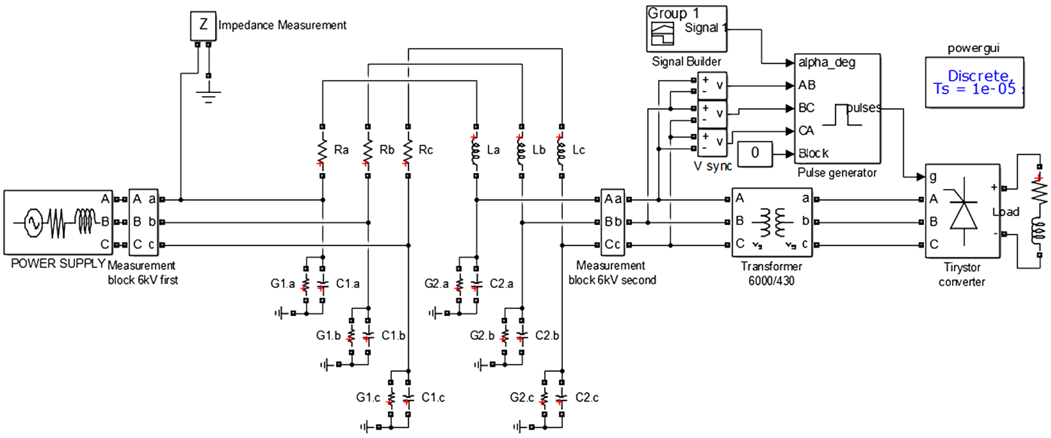

Fig. 2. Three-phase power supply system diagram

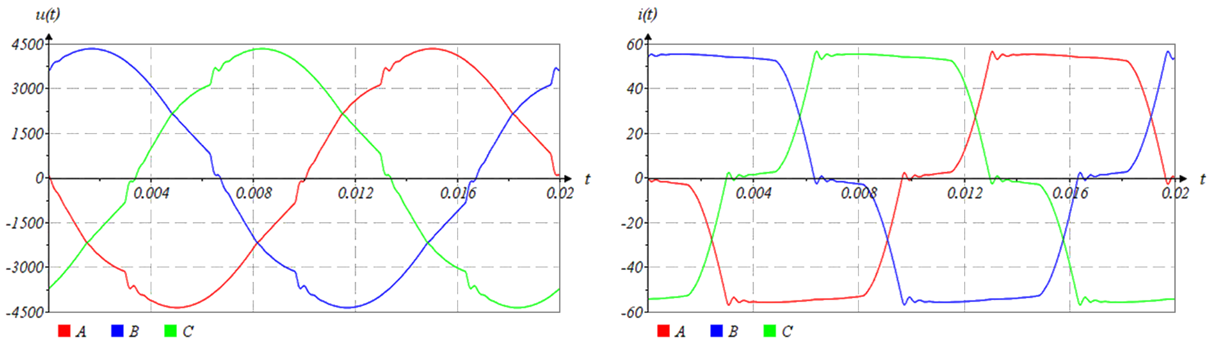

Fig. 3. Cable line input voltages and currents

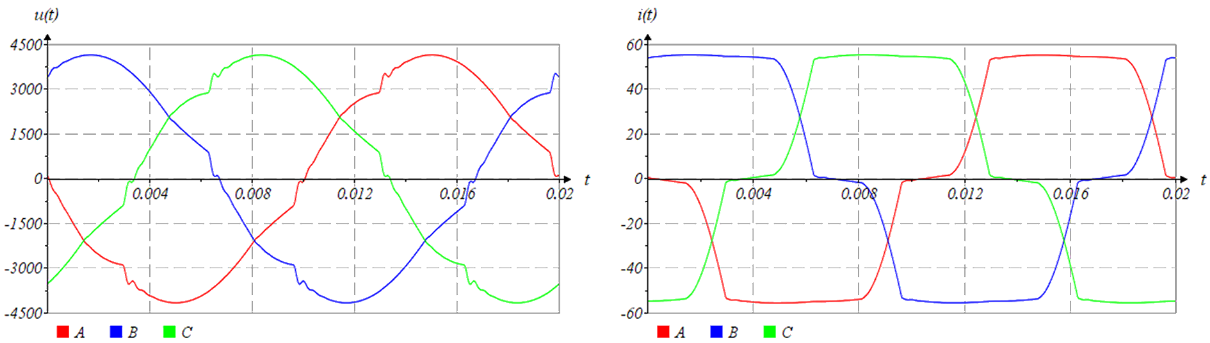

Fig. 4. Cable line output voltages and currents

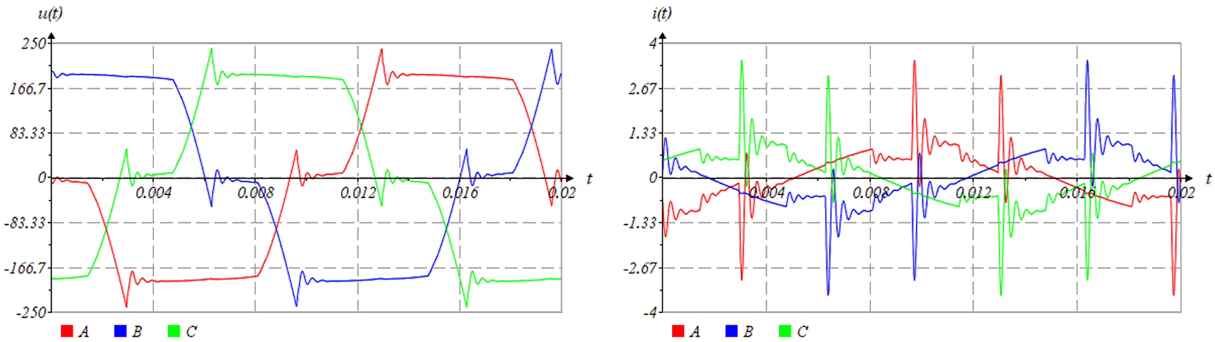

Fig. 5. Difference between input and output voltages and currents of the cable line

damental harmonic shape and also has a high level of damped oscillatory processes that appear approximately at the moments of impulsive changes in the input and output voltages, i. e. the change in currents is more influenced by the change in voltage.

Fig. 6 shows time diagrams of the change in the power of a cable line over time, as the difference in instantaneous power at the line's input and output. This power is highly non-sinusoidal, indicating the effect of higher harmonics amplification in the line itself.

Consider the power distribution in the cable line replacement circuit elements. The power of active conduction *G* (Fig. 7) has a familiar constant character, because it is an active power. The degree of distortion of this power relative to the distortion of the total line power is lower, and is related to the degree of voltage distortion according to expression (13).

Due to the accumulation of charge, the capacitance *C* leads to an increase in energy consumption. Also, the insulation leads capacitance to additional ways of energy leakage through the insulation, which further affects the growth of the insulating conductivity.

The resulting graphs show how changes in the voltage lead to sharp current fluctuations, i. e. the voltage affects the capacitance not so much by its quantitative change as by the rate of change of the processes that occur in it. If we take into account the fact that current changes mainly occur in the capacitance, let us consider the power graph arising in the cable line on this element (Fig. 8).

In contrast to the power of the conductivity *G*, the power in the capacitance *C* enters the negative region, i. e. the charge accumulated by the capacitance is constantly changing but with different intensity, power graph which causes asymmetry with respect to the time axis.

Similarly to the conductivity element *G*, the power in the active resistance of the line *R* is familiarly constant (Fig. 9). As can be seen from the power level, this power is dominant, and its average value corresponds to the level of power losses in the line.

The cable line power diagram inductance *L* is shown in Fig. 10. As can be seen from the diagram, significant current change fronts cause large power pulses, while under the influence of a significant non-sinusoidal current, power fluctuations are sharply variable.

According to the method described above, we will identify the cable line parameters by power components. The identification results are summarized in the table below.

The Table analysis shows that the largest error in determining the parameter is inherent in the active conductivity *G*, which may be due to the low value of this parameter and the corresponding low power value.

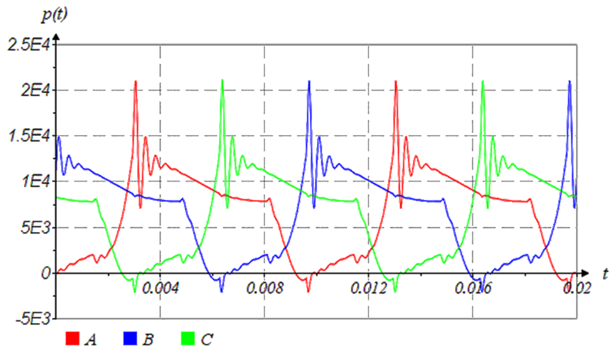

Fig. 6. Cable line power in three phases

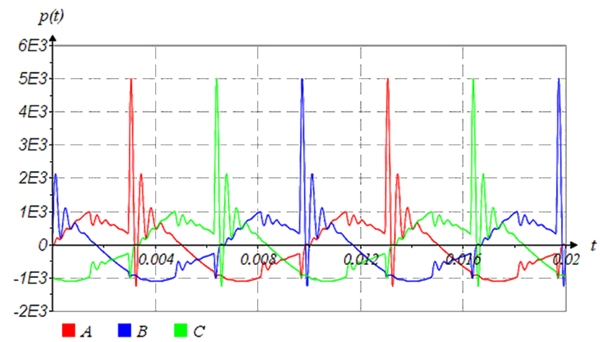

Fig. 8. Power on the capacitance element C in three phases

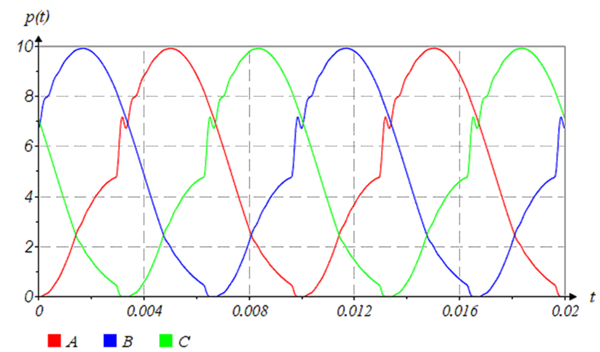

Fig. 7. Power on conductive elements G in three phases

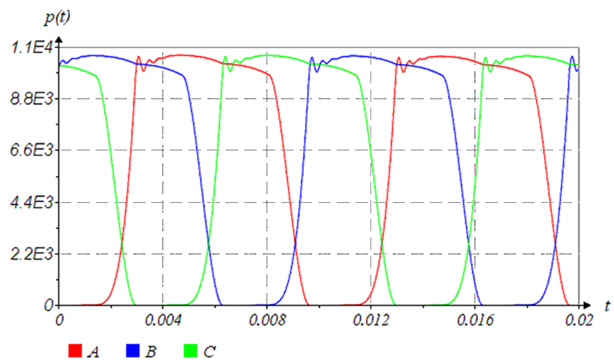

Fig. 9. Power on resistance elements R in three phases

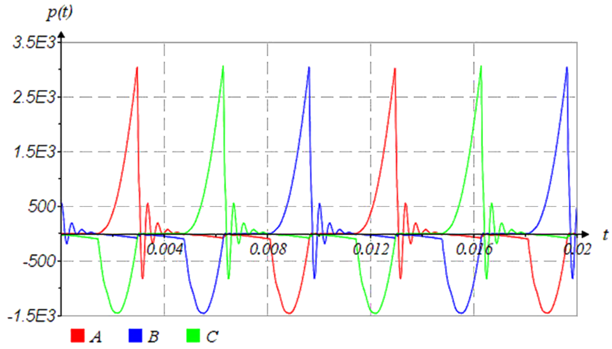

Fig. 10. Power on inductor elements L in three phases

Table

Results of identifying the parameters of the substitution scheme

Parameter	Output value	Calculated value	Error, %
Phase A			
G_A, µS	2.874	3.08	–6.69
C_A, µF	0.696	0.696	0.00
R_A, Ohm	3.46	3.462	–0.06
L_A, mH	1.09	1.099	–0.83
Phase B			
G_B, µS	2.874	2.65	7.79
C_B, µF	0.696	0.698	–0.29
R_B, Ohm	3.46	3.471	–0.32
L_B, mH	1.09	1.087	0.28
Phase C			
G_C, µS	2.874	3.047	–6.02
C_C, µF	0.696	0.699	–0.43
R_C, Ohm	3.46	3.462	–0.06
L_C, mH	1.09	1.071	1.74

Conclusions and direction of further research. Based on the analysis results of known studies, it has been established that existing methods for determining the parameters of a cable line replacement scheme require its disconnection from the power supply and load systems.

A method for determining the parameters of a cable line replacement scheme using the power components of its elements is proposed, which differs in that the use of power can increase the total number of system equations for determining the parameters.

When determining the instantaneous reactive elements power of the cable line replacement scheme, it is found that when calculating the instantaneous power, there is a feature of taking into account the voltage harmonic number, depending on the combination of harmonic numbers.

The study of the proposed method for determining the cable line replacement scheme parameters by power components, based on the model created in the visual programming package, allowed us to establish that the largest error in determining the parameters is inherent in the active conductivity.

The proposed method can be developed for sectioning U-shaped line replacement schemes to determine changes in the cable line replacement scheme parameters during its operation without disconnecting the line, unlike existing methods.

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Визначення параметрів еквівалентної схеми кабельної лінії за компонентами моментальної потужності

О. В. Бялобржеський[*1], *О. В. Тодоров*[1], *А. О. Постіл*[1], *М. А. Беззуб*[1], *А. А. Сулим*[2]

1 – Кременчуцький національний університет імені Михайла Остроградського, м. Кременчук, Україна
2 – Державне підприємство «Український науково-дослідний інститут вагонобудування», м. Кременчук, Україна
[*] Автор-кореспондент e-mail: seemal@kdu.edu.ua

Мета. Розробка методу визначення параметрів схеми заміщення кабельної лінії за складовими її миттєвої потужності.

Методика. Визначення невідомих параметрів режиму кабельної лінії з використанням методу гармонійного балансу. Визначення параметрів елементів П-подібної схеми заміщення виконується з використанням гармонік потужностей та їх балансу на відповідних частотах. Для частотно-залежних елементів ураховувано, що одна й та сама гармоніка потужності може бути утворена різними гармоніками струму й напруги.

Результати. Запропоновано метод визначення параметрів схеми заміщення кабельної лінії з використанням складових потужності її елементів, який відрізняється тим, що за рахунок використання потужності може бути збільшена загальна кількість рівнянь системи для визначення параметрів. Дослідження пропонованого методу визначення параметрів схеми заміщення кабельної лінії за складовими потужності, на підставі моделі складеної у пакеті візуального програмування, дозволи встановити, що найбільша похибка визначення параметрів властива активній провідності.

Наукова новизна. За умови визначення миттєвої потужності реактивних елементів схеми заміщення кабельної лінії виявлено, що під час розрахунку миттєвої потужності виникає особливість урахування номеру гармоніки напруги в залежності від комбінації номерів гармонік.

Практична значимість. Пропонований метод може бути розвинутий на секціонуванні П-подібні схеми заміщення лінії для визначення зміни параметрів схеми заміщення кабельної лінії під час її експлуатації без відключення лінії, на відміну від існуючих методів.

Ключові слова: *кабельна лінія, потужність, напруга, гармоніки, ортогональні складові, частота гармоніки*

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