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IDENTIFICATION OF GENERALIZED LINEAR LOAD IN THREE-PHASE THREE-WIRE NETWORK IN THE PROBLEM OF THE DISTRIBUTION OF ACTUAL CONTRIBUTIONS AT THE POINT OF COMMON COUPLING

Purpose. To perform structural and parametric identification of generalized load equivalent circuit of three-phase three-wire load in the network in the space of phase components. *Methodology.* Underlying structural identification methods are matrix analysis of electrical circuits. *Parametric identification* is based on the basic laws of electrical engineering. *Results.* The structure of a generalized load equivalent circuit is composed in three independent nodes. An approximate method for determining its parameters is proposed. The estimation error determination undistorted and distorted parts of the parameters of generalized load equivalent circuit. *Originality.* Approximate determination of equivalent circuit parameters are based on the results of a single measurement of voltages and phase currents. *Practical value.* The proposed replacement structure and a method for determining its parameters of the circuit can be used in the problem of the distribution of actual contributions at the point of common coupling. References 7, tables 1, figures 4.

Key words: equivalent circuit of linear generalized load, actual contribution, point of common coupling.

На основе матричного метода анализа электрических цепей определена структура эквивалентной схемы замещения обобщенной нагрузки. Предложен способ приближенного определения параметров эквивалентной схемы замещения обобщенной нагрузки. Выполнен анализ ошибок приближенного определения параметров эквивалентной схемы замещения обобщенной нагрузки применительно к задаче распределения фактических вкладов в точке общего присоединения. Библи. 7, табл. 1, рис. 4.

Ключевые слова: эквивалентная схема замещения линейной обобщенной нагрузки, фактический вклад, точка общего присоединения.

Introduction. The asymmetry and deviation of voltages is one of the main characteristics of electric power, which in most cases do not meet its quality [1]. Consequences of electrical consumption and lower quality of transmission power are well known [2], and, ultimately, to reduce financial losses [3]. Determination of the actual contributions to the reduction of electric power quality at the point of common coupling (PCC) is a solution of the problem of the distribution of compensation for economic loss to the injured party by all electricity market participants.

Problem definition. Existing methods for the distribution of actual contributions [4], irrespective of the implementation of the selected mathematical space, have a common problem. It is an adequate representation and parameterization of the generalized equivalent circuit load. So, in the space of generalized symmetrical components are load in the form of a set of current source or EMF with its resistance, which corresponds to the Norton or Thevenin equivalent circuits. In the space of phase components can restrict passive elements, where a clear opinion on the equivalent circuit of the structure in relation to the actual distribution of the contributions is not the problem. At asymmetrical load using the method of symmetrical components does not give any advantages over the phase space components. On this basis, the paper discusses the definition of the structure and parameters of equivalent circuit linear distorting the generalized three-phase three-wire load in networks within the space of phase components.

The goal of investigations is to develop an approach for generalized linear identification in three-phase three-wire load in the network within the space of phase components for task allocation of actual contributions to the current of common coupling.

Results of investigations. We consider the power supply system (PSS) with a dedicated load relatively PCC which made measurement of indicators of quality of electric energy (Fig. 1,a). We assume that all the elements of the electric power system and electric energy receivers generalized stress can cause only linear (sinusoidal) voltage distortion. Then, the equivalent circuit can be represented PSS such as active and passive elements connection (Fig. 1,b). In addition, we take the assumption of neglecting the mutual impedance and conductivity of individual PSS components.

According to the method of nodal potentials the total equivalent circuit of power system and the generalized load described by the following matrix equation:

$$\begin{bmatrix} Y_{aa} & Y_{ab} \\ Y_{ba} & Y_{bb} \end{bmatrix} \times \begin{bmatrix} \Phi_a \\ \Phi_b \end{bmatrix} = \begin{bmatrix} J_a \\ J_b \end{bmatrix}, \quad (1)$$

where a is the serial number of the last node from the side of the equivalent circuit of power system; b is the number of independent nodes in the overall equivalent scheme of the electric power system and the generalized load.

The solution of equation (1) relative the sub-matrix $\vec{\Phi}_a$ in the absence of active elements in the equivalent circuit of the generalized load is as follows:

$$(Y_{aa} + Y_{eq}) \times \vec{\Phi}_a = \vec{J}_a, \quad (2)$$

where Y_{eq} is matrix of nodal conductivities of equivalent generalized load which characterizes the structure of its equivalent circuit.

The matrix Y_{eq} is determined as follows:

$$Y_{eq} = -Y_{ab} \times Y_{bb}^{-1} \times Y_{ba}. \quad (3)$$

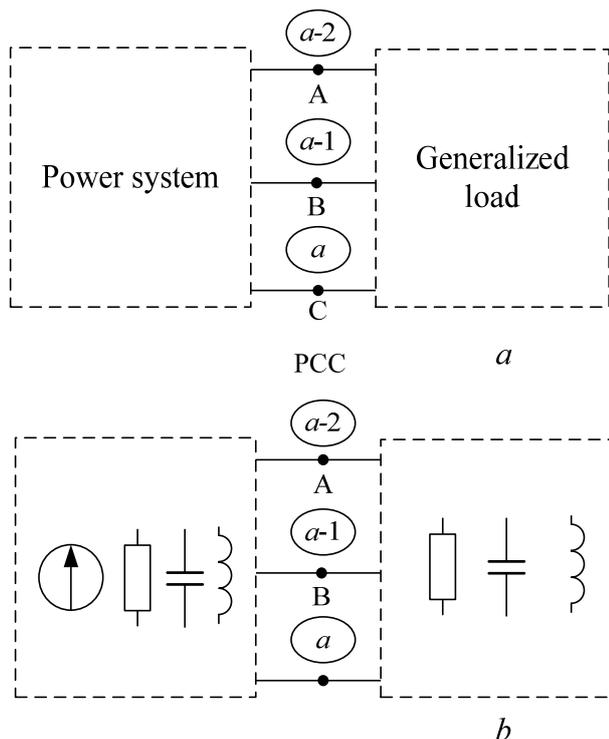


Fig. 1. Power supply system: *a* – structural circuit relative PCC; *b* – schematic diagram of the replacement of the power system and the generalized load

A feature of the matrix Y_{eq} in our case is that all the elements in it, except for the block elements of the dimension $[3 \times 3]$, zero. This implies that an equivalent substitution of generalized load circuit must have three independent nodes. This condition corresponds to the structure of the equivalent circuit shown in Fig. 2.

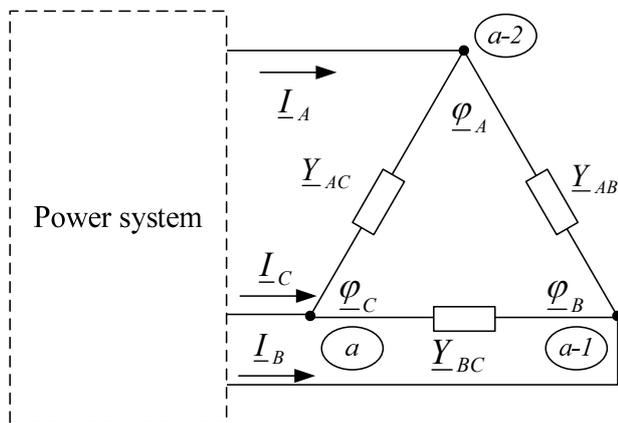


Fig. 2. Structure of the equivalent circuit of the generalized load

Let us consider a problem of the determination of the generalized load equivalent circuit parameters. Initial data are measured in the PCC phase currents (I_A , I_B and I_C) and linear voltages (U_{AB} , U_{BC} and U_{AC}).

Parameters of the equivalent circuit and measured mode parameters are interconnected as follows:

$$\begin{cases} U_{AB} \cdot Y_{AB} + 0 \cdot Y_{BC} + U_{AC} \cdot Y_{AC} = I_A; \\ U_{BA} \cdot Y_{AB} + U_{BC} \cdot Y_{BC} + 0 \cdot Y_{AC} = I_B. \end{cases} \quad (4)$$

The system (4) consisting of two linear algebraic equations and containing three unknowns (Y_{AB} , Y_{BC} and Y_{AC}) is uncertain and joint. Its general solution has the form

$$\begin{cases} Y_{AB} = (I_A - U_{AC} \cdot Y_{AC}) / U_{AB}; \\ Y_{BC} = -(I_C + U_{AC} \cdot Y_{AC}) / U_{BC}. \end{cases} \quad (5)$$

To determine unknown conductivities Y_{AB} , Y_{BC} and Y_{AC} it is possible to resort to a redefinition of the system (5) by the use of two independent data, for example, successive measurements. Applying the least squares method to such a system of equations, unknown conductivity will be determined as follows:

$$\vec{Y} = (U^T U)^{-1} U^T \vec{I}, \quad (6)$$

где U is the matrix of measured voltages; \vec{I} is the column matrix of measured currents; \vec{Y} is the column matrix of unknown conductivities.

Using the above approach determine the unknown conductivities requires compliance with the following conditions. Measured parameters mode must display two different PSS condition caused by changes only from the electric power system. From a practical point of view, this situation is unlikely in PSS so many researchers, for example, [5, 6], propose to conduct active experiment based on forced switching capacitor banks in the PCC. Taking into account the method of measuring the parameters of electrical energy quality, where the minimum measurement interval mode settings begins with 0.2 s this approach is unacceptable. In addition, the results of mathematical modeling show high sensitivity of the solution (6) to minor changes in the state of generalized load, as well as the magnitude of the disturbance from the power system. As a consequence, an adequate definition of the equivalent circuit parameters of the generalized load according to the expression (6) in a real operation is not technically feasible.

We consider the possibility of determining the approximate equivalent circuit parameters of the generalized load. For this purpose, we turn to its equivalent circuit represented as a star connection of elements (Fig. 3).

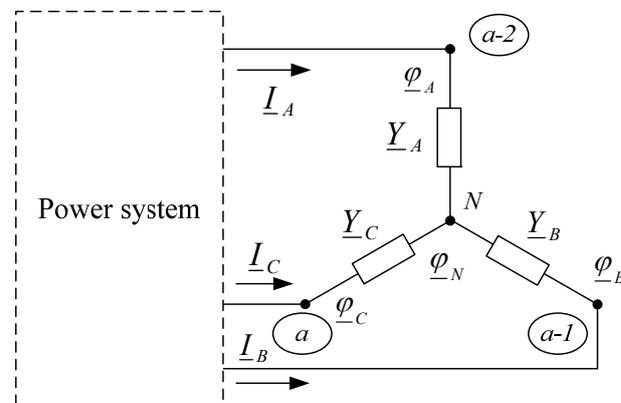


Fig. 3. Equivalent circuit of the generalized load with star connection of elements

The considered equivalent circuit with four nodes is the described by the following system of three equations:

$$\begin{cases} \underline{U}_A \cdot \underline{Y}_A = \underline{I}_A; \\ \underline{U}_B \cdot \underline{Y}_B = \underline{I}_B; \\ \underline{U}_C \cdot \underline{Y}_C = \underline{I}_C. \end{cases} \quad (7)$$

As it is known, an accurate measurement of the phase voltages of three-phase three-wire in the networks due to a physical lack of a neutral point, generally can not be performed. Therefore, for an approximate determination of the phase voltages use the measured values of the line voltages:

$$\begin{cases} \underline{U}_A^{\approx} = (\underline{U}_{AB1} \cdot e^{-j30} + \underline{U}_{AB2} \cdot e^{j30}) / \sqrt{3}; \\ \underline{U}_B^{\approx} = \underline{U}_{BA} + \underline{U}_A^{\approx}; \\ \underline{U}_C^{\approx} = \underline{U}_{CB} + \underline{U}_B^{\approx}, \end{cases} \quad (8)$$

where \underline{U}_{AB1} and \underline{U}_{AB2} are the linear voltages of direct and inverse sequences, respectively.

The error of the determination of phase voltages for the equivalent circuit of Fig. 3 will be determined by the difference of exact φ_N and approximate $(\underline{U}_A^{\approx} + \underline{U}_B^{\approx} + \underline{U}_C^{\approx})/3$ values of potentials of the point N (Fig. 4):

$$\Delta\varphi = \varphi_N - (\underline{U}_A^{\approx} + \underline{U}_B^{\approx} + \underline{U}_C^{\approx})/3. \quad (9)$$

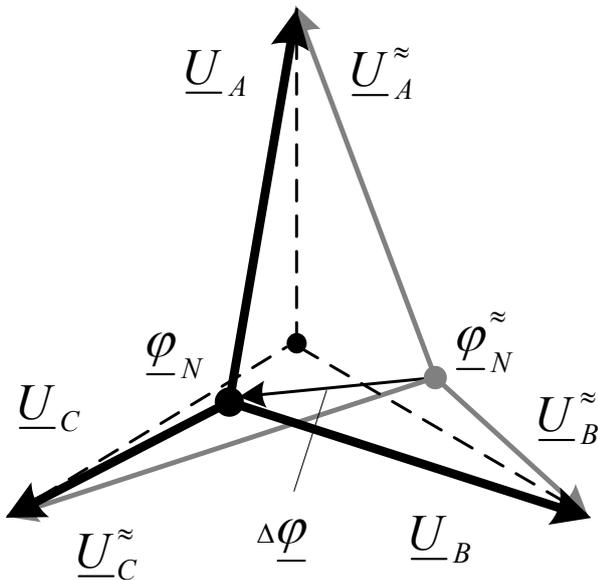


Fig. 4. Exact and approximate values of phase voltages for the equivalent circuit of the generalized load with star connection of elements (Fig. 3)

So, approximate values of conductivities $\underline{Y}_A^{\approx}$, $\underline{Y}_B^{\approx}$ and $\underline{Y}_C^{\approx}$, calculated by (7) taking into account (8) connected with their exact values by the following equality:

$$\underline{Y}_{ph}^{\approx} = \underline{Y}_{ph} - \underline{Y}_{ph} \cdot \Delta\varphi / \underline{U}_{ph}^{\approx}, \quad (10)$$

where the symbol "ph" corresponds to phase A, B or C.

To solve the problem of the distribution of phase values the basic is dividing of the equivalent circuit into

nondisturbing and disturbing parts. Here, from the point of view of phase conductivities determination, the most sensitive for this dividing are *nondisturbing* and *disturbing* parts used for the phase values determination by the voltage asymmetry:

$$\begin{cases} \underline{Y}_{ph}^{nondis} = (\underline{Y}_A + \underline{Y}_B + \underline{Y}_C) / 3; \\ \underline{Y}_{ph}^{dis} = \underline{Y}_{ph} - \underline{Y}_{ph}^{nondis}. \end{cases} \quad (11)$$

From here, we conduct analysis of error of determination of nondisturbing and disturbing parts of the generalized load equivalent circuit parameters for two characterized cases when on buses of balanced and nonbalanced loads there is asymmetric voltage.

At the balanced load with asymmetric voltage errors of determination of $\underline{Y}_{ph}^{nondis}$ and \underline{Y}_{ph}^{dis} are:

$$\delta \underline{Y}_{ph}^{nondis} = \frac{\underline{Y}_{ph} \cdot \Delta\varphi}{3} \cdot \left(\frac{1}{\underline{U}_A^{\approx}} + \frac{1}{\underline{U}_B^{\approx}} + \frac{1}{\underline{U}_C^{\approx}} \right); \quad (12)$$

$$\delta \underline{Y}_{ph}^{dis} = \underline{Y}_{ph} \cdot \Delta\varphi / \underline{U}_{ph}^{\approx} - \frac{\underline{Y}_{ph} \cdot \Delta\varphi}{3} \cdot \left(\frac{1}{\underline{U}_A^{\approx}} + \frac{1}{\underline{U}_B^{\approx}} + \frac{1}{\underline{U}_C^{\approx}} \right). \quad (13)$$

We simplify the factor $\left(\frac{1}{\underline{U}_A^{\approx}} + \frac{1}{\underline{U}_B^{\approx}} + \frac{1}{\underline{U}_C^{\approx}} \right)$ assuming

that $\left| \underline{U}_{A2}^{\approx} / \underline{U}_{A1}^{\approx} \right| \ll 1$:

$$\begin{aligned} & \left(\frac{1}{\underline{U}_{A1}^{\approx} + \underline{U}_{A2}^{\approx}} + \frac{1}{\underline{U}_B^{\approx}} + \frac{1}{\underline{U}_C^{\approx}} \right) \approx \\ & \approx - \left(\frac{\underline{U}_{A2}^{\approx}}{(\underline{U}_{A1}^{\approx})^2} + \frac{\underline{U}_{B2}^{\approx}}{(\underline{U}_{B1}^{\approx})^2} + \frac{\underline{U}_{C2}^{\approx}}{(\underline{U}_{C1}^{\approx})^2} \right) = - \frac{3 \cdot \underline{U}_{A2}^{\approx}}{(\underline{U}_{A1}^{\approx})^2}. \end{aligned} \quad (14)$$

Then, taking into account (14) the approximate value of $\delta \underline{Y}_{ph}^{nondis}$ is:

$$\delta \underline{Y}_{ph}^{nondis} \approx - \underline{Y}_{ph} \cdot \Delta\varphi \cdot \frac{\underline{U}_{A2}^{\approx}}{(\underline{U}_{A1}^{\approx})^2}. \quad (15)$$

Taking into account that factor $\underline{U}_{A2}^{\approx} / (\underline{U}_{A1}^{\approx})^2$ in two order reduces the result of product $\underline{Y}_{ph} \cdot \Delta\varphi$ в (15), the value of error $\delta \underline{Y}_{ph}^{nondis}$ can be considered as tending to zero. For example, at $|\Delta\varphi|$ equal to 10 % of the direct sequence phase value module ($|\underline{U}_{A1}^{\approx}|$) and $|\underline{U}_{A2}^{\approx}|$ equal to 4

% of $\left| \underline{U}_{A1}^{\approx} \right|^2$ the error of determination $\underline{Y}_{ph}^{nondis}$ of balanced load will have order of $-0,004 \cdot \underline{Y}_{ph}$ which corresponds in relative units to -0.4 %.

Error $\delta \underline{Y}_{ph}^{dis}$ taking into account (14) will be approximately determined as follows:

$$\delta Y_{-ph}^{dis} \approx Y_{-ph} \cdot \Delta \varphi \cdot \left(\frac{1}{U_{-ph}} + \frac{U_{A2}^{\approx}}{(U_{A1}^{\approx})^2} \right). \quad (16)$$

Taking into account that $U_{A2}^{\approx}/(U_{A1}^{\approx})^2$ is the value of the second order with respect to $1/U_{-ph}$, we can write:

$$\delta Y_{-ph}^{dis} \approx Y_{-ph} \cdot \frac{\Delta \varphi}{U_{-ph}}. \quad (17)$$

From (17) it can be seen that the value of error δY_{-ph}^{dis} will be determined by the value $\Delta \varphi$. For example, at $|\Delta \varphi| = 0.1 |U_{-ph}^{\approx}|$ the order of the error δY_{-ph}^{dis} is $0.1 Y_{-ph}$ at the true value $Y_{-ph}^{dis} = 0$.

At the unbalanced load with asymmetric voltage we have:

$$\delta Y_{-ph}^{nondis} = \frac{1}{3} \cdot \left(\begin{array}{l} Y_A \cdot \left| \frac{\Delta \varphi}{U_A^{\approx}} \right| \cdot e^{j(\alpha - \varphi_A)} + Y_B \cdot \left| \frac{\Delta \varphi}{U_B^{\approx}} \right| \times \\ \times e^{j(\alpha - \varphi_B)} + Y_C \cdot \left| \frac{\Delta \varphi}{U_C^{\approx}} \right| \cdot e^{j(\alpha - \varphi_C)} \end{array} \right). \quad (18)$$

$$\delta Y_{-ph}^{dis} = Y_{-ph} \cdot \Delta \varphi / U_{-ph} - \frac{1}{3} \cdot \left(\begin{array}{l} Y_A \left| \frac{\Delta \varphi}{U_A^{\approx}} \right| \cdot e^{j(\alpha - \varphi_A)} + \\ + Y_B \left| \frac{\Delta \varphi}{U_B^{\approx}} \right| \cdot e^{j(\alpha - \varphi_B)} + Y_C \left| \frac{\Delta \varphi}{U_C^{\approx}} \right| \cdot e^{j(\alpha - \varphi_C)} \end{array} \right), \quad (19)$$

where $\alpha = \arg(\Delta \varphi)$; $\varphi_{ph} = \arg(U_{-ph}^{\approx})$.

Let us assume that phase voltages values (U_A^{\approx} , U_B^{\approx} и U_C^{\approx}) are approximately symmetrical. Then, with the possibility of an arbitrary rotation of the system of vectors, we have:

$$\begin{aligned} & Y_A \left| \frac{\Delta \varphi}{U_A^{\approx}} \right| \cdot e^{j0} + Y_B \left| \frac{\Delta \varphi}{U_B^{\approx}} \right| \cdot e^{j120} + Y_C \left| \frac{\Delta \varphi}{U_C^{\approx}} \right| \cdot e^{j240} \approx \\ & \approx \frac{|\Delta \varphi|}{|U_{-ph}^{\approx}|} \cdot [Y_A^{dis} \cdot e^{j0} + Y_B^{dis} \cdot e^{j120} + Y_C^{dis} \cdot e^{j240}] \end{aligned} \quad (20)$$

Assuming that arguments of disturbing parts of conductivities (Y_A^{dis} , Y_B^{dis} and Y_C^{dis}) are such that their multiplication on unit vectors e^{j0} , e^{j120} and e^{j240} in a sum give a vector $|Y_A^{dis}| + |Y_B^{dis}| + |Y_C^{dis}|$, the error module δY_{-ph}^{nondis} for the case of unbalanced load can be estimated by the following inequality:

$$\left| \delta Y_{-ph}^{nondis} \right| < \frac{|\Delta \varphi|}{|U_{-ph}^{\approx}|} \cdot |Y_{-ph}^{dis} \max|, \quad (21)$$

where $Y_{-ph}^{dis} \max$ is the maximal phase disturbing conductivity which for the limit case (asymmetric load with star connection (Fig.3) set by one shoulder) equals to:

$$Y_{-ph}^{dis} \max = \frac{2}{3} Y_{-ph}. \quad (22)$$

So, for $|\Delta \varphi| = 0.1 |U_{-ph}^{\approx}|$ we have

$$\left| \delta Y_{-ph}^{nondis} \right| < 0,067 \cdot |Y_{-ph}|.$$

Let us consider the error δY_{-ph}^{dis} taking into account that the second summand in (19) is δY_{-ph}^{nondis} (21):

$$\delta Y_{-ph}^{dis} \approx \frac{\Delta \varphi}{U_{-ph}^{\approx}} \cdot (Y_{-ph} - \delta Y_{-ph}^{nondis}). \quad (23)$$

Taking into account (22), the module of the maximum error value δY_{-ph}^{dis} can be estimated by the following inequality:

$$\left| \delta Y_{-ph}^{dis} \max \right| < \frac{|\Delta \varphi|}{|U_{-ph}^{\approx}|} \cdot \frac{5}{3} |Y_{-ph}|. \quad (24)$$

Quantitatively, at $|\Delta \varphi| = 0.1 |U_{-ph}^{\approx}|$,

$$\left| \delta Y_{-ph}^{dis} \max \right| < 0,17 \cdot |Y_{-ph}|.$$

From the carried out analysis of errors δY_{-ph}^{nondis} and δY_{-ph}^{dis} it follows that disturbing parts of conductivities of balanced and unbalanced generalized load can be determined with high accuracy. Determination of disturbing parts is characterized by significant errors commensurate with the exact values of the unknown quantities.

Conclusions.

The structure of the equivalent circuit of substitution generalized linear loads in three-phase three-wire network is determined by three independent units, which corresponds to the connection diagram of elements in a triangle. The exact definition of the equivalent circuit parameters based on the methodology for measuring the quality parameters of electric energy is not technically feasible. A method for the approximate determination of the parameters of the equivalent circuit of substitution generalized linear load based on an approximate determination of the phase voltages. Errors calculating nondisturbing parts equivalent circuit parameters of generalized linear substitution loads are characterized by small quantities, which can be neglected. Errors calculation distorting parts may reach values comparable with the exact values.

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