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 of 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.

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

\[
\begin{pmatrix}
Y_{aa} & Y_{ab} \\
Y_{ba} & Y_{bb}
\end{pmatrix}
\begin{pmatrix}
\Phi_a \\
\Phi_b
\end{pmatrix} =
\begin{pmatrix}
J_a \\
J_b
\end{pmatrix},
\]

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 \( \Phi_a \) in the absence of active elements in the equivalent circuit of the generalized load is as follows:

\[
Y_{aa} + Y_{eq} \times \Phi_a = \mathbf{J}_a,
\]

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:

\[
Y_{eq} = -Y_{ab} \times Y_{bb}^{-1} \times Y_{ba}.
\]
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.

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:

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

where $U$ 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).
The considered equivalent circuit with four nodes is the described by the following system of three equations:

\[
\begin{align*}
U_A & = Y_A \cdot I_A; \\
U_B & = Y_B \cdot I_B; \\
U_C & = Y_C \cdot I_C.
\end{align*}
\]  
(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:

\[
\begin{align*}
U_A &= \left( U_{AB1} \cdot e^{-j30} + U_{AB2} \cdot e^{j30} \right) / \sqrt{3}; \\
U_B &= U_{BA} + U_A^\infty; \\
U_C &= U_{CB} + U_A^\infty.
\end{align*}
\]  
(8)

where \( U_{AB1} \) and \( U_{AB2} \) 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 \( \phi_N \) and approximate \( \left( U_A^\infty + U_B^\infty + U_C^\infty \right)/3 \) values of potentials of the point \( N \) (Fig. 4):

\[
\Delta \phi = \phi_N - \left( U_A^\infty + U_B^\infty + U_C^\infty \right)/3.
\]  
(9)

\[
\begin{align*}
U_A^\infty &= U_{A1}^\infty + U_{A2}^\infty; \\
U_B^\infty &= U_{B1}^\infty + U_{B2}^\infty; \\
U_C^\infty &= U_{C1}^\infty + U_{C2}^\infty.
\end{align*}
\]

\[
\begin{align*}
U_A^\infty &= U_{A1}^\infty + U_{A2}^\infty; \\
U_B^\infty &= U_{B1}^\infty + U_{B2}^\infty; \\
U_C^\infty &= U_{C1}^\infty + U_{C2}^\infty.
\end{align*}
\]

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 \( Y_A^\infty \), \( Y_B^\infty \) and \( Y_C^\infty \), calculated by (7) taking into account (8) connected with their exact values by the following equality:

\[
Y_{ph}^\infty = Y_{ph} - Y_{ph} \cdot \Delta \phi / U_{ph}^\infty,
\]  
(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:

\[
\begin{align*}
Y^\text{nondis}_{ph} &= \left( Y_A + Y_B + Y_C \right)/3; \\
Y^\text{dis}_{ph} &= Y_{ph} - Y^\text{nondis}_{ph}.
\end{align*}
\]  
(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 unbalanced loads there is asymmetric voltage.

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

\[
\delta Y^\text{nondis}_{ph} = \frac{Y^\text{ph} \cdot \Delta \phi}{3} \left( \frac{1}{U_A} + \frac{1}{U_B} + \frac{1}{U_C} \right);  \\
\delta Y^\text{dis}_{ph} = \frac{Y^\text{ph} \cdot \Delta \phi}{3} \left( \frac{1}{U_A} + \frac{1}{U_B} + \frac{1}{U_C} \right).
\]  
(12)

We simplify the factor \( \left( \frac{1}{U_A} + \frac{1}{U_B} + \frac{1}{U_C} \right) \) assuming

\[
\left| \frac{U^\infty_A}{U^\infty_1} \right| << 1:
\]  
(14)

\[
\delta Y^\text{nondis}_{ph} = -Y_{ph} \cdot \Delta \phi \cdot \frac{U^\infty_A}{U^\infty_1};
\]  
(15)

Taking into account that factor \( \frac{U^\infty_A}{U^\infty_1} \) in two order reduces the result of product \( Y_{ph} \cdot \Delta \phi \) b (15), the value of error \( \delta Y^\text{nondis}_{ph} \) can be considered as tending to zero. For example, at \( \left| \Delta \phi \right| \) equal to 10 % of the direct sequence phase value module \( \left| U^\infty_1 \right| \) and \( \left| U^\infty_2 \right| \) equal to 4 % of \( \left| U^\infty_1 \right| \) the error of determination \( Y^\text{nondis}_{ph} \) of balanced load will have order of \(-0.004 \cdot Y_{ph} \) which corresponds in relative units to -0.4 %.

Error \( \delta Y^\text{dis}_{ph} \) taking into account (14) will be approximately determined as follows:
where $Y_{ph}^{dis}$ is the maximal phase disturbing conductivity which for the limit case (asymmetric load with star connection (Fig.3) set by one shoulder) equals to:

$$Y_{ph}^{dis} = \frac{2}{3} Y_{ph}.$$  

(22)

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

$$\delta Y_{ph}^{dis} < \frac{|A\phi|}{|U_{ph}|} \frac{5}{3} Y_{ph}.  \quad (24)$$

Quantitatively, at $|A\phi| = 0.1 \left| \frac{U_{ph}}{Y_{ph}} \right|$ we have

$$\delta Y_{ph}^{dis} < 0.17 \cdot Y_{ph}.  \quad (23)$$

From the carried out analysis of errors $\delta Y_{ph}^{nondis}$ and $\delta Y_{ph}^{dis}$ 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 disturbing parts may reach values comparable with the exact values.

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Received 29.09.2016

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How to cite this article:
Sayenko Yu.L., Kalyuzhniy D.N. 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. Electrical engineering & electromechanics, 2016, no.6, pp. 65-69. doi: 10.20998/2074-272X.2016.6.11.