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Analytical method of determining conditions for full compensation of reactive power in the power supply system

Goal. *The purpose of the article is the development of an analytical method for determining the conditions for achieving full compensation in the generalized power supply system based on the use of substitute circuits, which are obtained using equivalent transformations of the topology of the original circuit.* ***Methodology.*** *The article proposes a methodology for replacing series reactive power compensation in high-voltage paths of the power supply system with parallel reactive power compensation in a low-voltage load node.* ***Results***. *An algorithm for successive transformations of the power supply circuit has been developed, which makes it possible to estimate the values of the capacitances of compensating capacitors, at which full compensation of reactive power in the system is achieved.* ***Originality.*** *The proposed analytical method for calculating the parameters of the compensation unit makes it possible to dispense with complex optimization computer methods and makes it possible to estimate the compensation capacities that fall on the share of the load and the network.* ***Practical value.*** *The proposed technique allows, using a simple algorithm, to determine with high accuracy the necessary parameters of the compensating device, which provide the optimal mode in the power supply system. The proposed algorithm can easily be implemented in a microcontroller system for automatic control of the modes of the power supply system.* References 15, table 1, figures 6.
Key words: **electrical system, reactive power, full compensation, search optimization, power factor, equivalent transformations, substitute circuit.**

Мета. *Метою статті є розробка аналітичного методу визначення умов досягнення повної компенсації в узагальненій системі електропостачання, на основі використання замінних схем, які отримані за допомогою еквівалентних перетворень топології вихідної схеми.* ***Методологія***. *У статті запропоновано методику заміни послідовної компенсації реактивної потужності у високовольтних трактах системи електропостачання на паралельну компенсацію реактивної потужності у вузлі навантаження низької напруги.* ***Результати***. *Розроблено алгоритм послідовних перетворень схеми живлення, що дає змогу оцінити значення ємностей компенсувальних конденсаторів, при яких досягається повна компенсація реактивної потужності в системі.* ***Оригінальність***. *Запропонована аналітична методика розрахунку параметрів вузла компенсації дозволяє відмовитися від складних комп'ютерних методів оптимізації та дає можливість оцінити компенсаційні можливості, які припадають на частку навантаження та мережі.* ***Практична цінність***. *Запропонована методика дозволяє за простим алгоритмом з високою точністю визначити необхідні параметри компенсаційного пристрою, які забезпечують оптимальний режим в системі електропостачання. Запропонований алгоритм легко реалізується в мікроконтролерній системі автоматичного керування режимами системи електропостачання.* Бібл. 15, табл. 1, рис. 6.
Ключові слова: **електрична система, реактивна потужність, повна компенсація, пошукова оптимізація, коефіцієнт потужності, еквівалентні перетворення, заступна схема.**

Introduction and problem definition. Reactive power compensation remains one of the main means of increasing the energy efficiency of power supply systems [1-6]. In Ukraine, under the current conditions of martial law, these issues should become one of the main factors in increasing the possibilities of emergency-free electricity supply, in particular, the compensation of reactive power will allow to relieve the load on electric networks and increase the efficiency of the systems as a whole [4, 5]. Along with the traditional approach of partial compensation of reactive power of loads, the mode of full compensation of reactive power deserves attention, in which in three-phase networks the inverse and zero symmetrical components are compensated [7-11], as well as the reactive power of the load directly and, in addition, the reactive power in the electrical network itself [12-14]. The latter are traditionally compensated by the so-called longitudinal compensation, in which compensating capacitors are connected in series in the power transmission line [1, 2]. But, as shown in [14], the compensation of the components caused by the inductances of the power transmission lines can be achieved by increasing the capacities of the transverse compensation capacitors, which shunt the load in the electricity collection nodes. In the general case, the determination of full compensation can be carried out with the help of search optimization [12, 13] by approximate numerical methods, since in essence it is necessary to solve a system of nonlinear equations, which contain both system parameters and currents with voltages, and they are interconnected by multiplication and division operations. This is characteristic, as will be shown below, for the variant of the single-line generalized circuit, which can be applied even when considering branched electrical networks. However, numerical methods are able to conduct research for specific numerical values that characterize the mode of full compensation. Analytical symbolic methods allow to conduct a qualitative analysis and obtain generalized results, recommendations and conclusions.

The goal of the article is to create an analytical method for determining the conditions for achieving full compensation in a generalized power supply system in order to simplify the methodology for determining the parameters of compensating devices and achieving results without using relatively complex procedures based on optimization algorithms.

The main part of the study. We consider the traditional power supply system with transverse compensation of reactive power [1-3, 5, 6, 10], which is shown in Fig. 1 in the generally accepted form for the electric power industry.

This system should be called a generalized power supply system, as it highlights the main components of the power supply system in compliance with the generally accepted conditions in the power industry. These conditions are, first of all, the assumption that a three-phase power supply system usually operates in a symmetrical mode, and therefore it is sufficient to analyze it in terms of only one of the three phases, and thanks to this, it is possible to consider the so-called single-line version of the system, i.e., a single-phase substitute circuit with one source voltage. Secondly, the parameters of the substitute circuit are redived to one side – either to the generator side, or to the load side, as is done, for example, when calculating short-circuit modes. Thirdly, the network, which can have a branched topology, is replaced by one complex active-inductive resistance based on the theorem on the equivalent active bipolar.

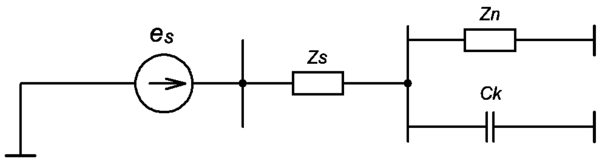

Fig. 1. Generalized single-line power supply system with reactive power compensator

In this circuit, e_s is the voltage source that generates and supplies electricity; Z_s is the complex active-inductive resistance that reflects the power transmission line and takes into account the internal resistance of the generator itself; Z_n is the complex active-inductive load; C_k is the capacity of a battery of capacitors that compensate for reactive power in the power supply system. Usually, quite approximate estimates of the value of this capacity are traditionally used in the electric power industry. It is determined as such that it is capable of compensating a certain given part of the reactive power of the load. This is due to the constant change in loads, for example, in the electricity supply networks of utility consumers.In addition, it is impossible to set the exact value of the capacity of the capacitor battery even when this value is determined, because it affects the discreteness of the values of the capacities of the individual capacitors that make up the battery. However, the development of semiconductor power electronics and means of automatic control of electrotechnical systems have trends in the digitalization of electronics and the transition to intelligent power supply systems [11], which will make it possible to solve these problems in general and provide an opportunity to achieve accurate parameters of compensating devices even in conditions of load variations. This refers to the use of controlled inductances with counter-switched thyristors, as well as power active filters with pulse width modulation.

Figure 2 shows a substitute circuit of a generalized power supply system with a compensator.

In this circuit, R_s and L_s are the active resistance and inductance of the power transmission line, which also include the corresponding parameters of the real generator; R_n and L_n are the active resistance and inductance of the load when the load is represented by a series equivalent.

The system of equations by the method of complex amplitudes describing this equivalent substitute circuit looks as follows in the basis of variables $\dot{I}_s$, $\dot{I}_n$, $\dot{U}_c$:

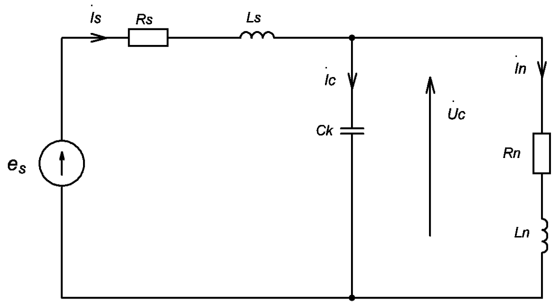

Fig. 2. Substitute circuit of the generalized power supply system with compensator

$$(R_s + j\omega L_s)\dot{I}_s + \dot{U}_c = \dot{e}_s ; \quad (1)$$

$$(R_n + j\omega L_n)\dot{I}_n - \dot{U}_c = 0 ; \quad (2)$$

$$\dot{I}_s - \dot{I}_n - j\omega C_k \dot{U}_c = 0 . \quad (3)$$

It should be noted that the system of these equations contains unknown currents $\dot{I}_s$, $\dot{I}_n$ and voltage $\dot{U}_c$, and in addition, the unknown quantity is the capacity C_k, which together with U_c forms the product $C\dot{U}_c$. This, in turn, leaves the system (1) – (3) linear, and in addition, three equations are no longer enough to uniquely determine $\dot{I}_s$, $\dot{I}_n$, $\dot{U}_c$ and C_k. In the search optimization method, this problem is solved by imposing additional conditions for reactive power compensation with the subsequent use of numerical algorithms using Newtonian methods or the algorithm optimization method, for example, a deformed polyhedron [12, 13].

We will apply the following stages of equivalent transformations of substitute circuits of the generalized power supply system.

Stage 1. Convert the series equivalent of the load with complex resistance $R_n + j\omega L_n$ into the parallel equivalent with complex conductivity $G_{n1} - jY_{n1}$:

$$G_{n1} - jY_{n1} = \frac{1}{R_n + j\omega L_n} = \frac{R_n}{R_n^2 + \omega^2 L_n^2} -$$

$$- j\frac{\omega L_n}{R_n^2 + \omega^2 L_n^2} = \frac{R_n}{R_n^2 + X_n^2} - j\frac{X_n}{R_n^2 + X_n^2} .$$

In addition, the capacitor C_k is replaced by two capacitors $C_k = C_1 + C_2$, where C_1 is designed to compensate the reactance of the purely load, and C_2 complements the compensation process to the level when the source e_s will not be connected to the reactive power, that is, the voltage and current phases of the sources will coincide and thereby complete compensation of the reactive power in the system will be achieved. The substitute obtained after stage 1 is shown in Fig. 3.

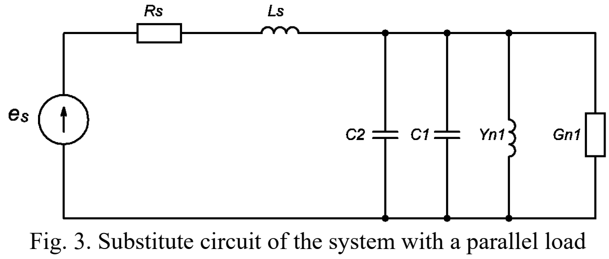

Fig. 3. Substitute circuit of the system with a parallel load equivalent and a distributed compensator

Stage 2. We determine the capacity of the capacitor C_1, which must compensate for the inductance of the parallel equivalent of the load:

$$j\omega C_1 - jY_{n1} = 0 \quad \text{or} \quad \omega C_1 = \frac{X_n}{R_n^2 + X_n^2},$$

where:

$$C_1 = \frac{X_n/\omega}{R_n^2 + X_n^2} = \frac{L_n}{R_n^2 + X_n^2}. \tag{4}$$

At the same stage, we can also get rid of two reactive elements in the substitute circuit (Fig. 3). We mean the inductance of the parallel equivalent of the load with conductivity Y_{n1} and the capacitor C_1, which fully compensates for this inductance. The sum of the conductances of these elements is zero, therefore, from the point of view of the method of complex amplitudes used here for analysis, these elements can simply be excluded from the circuit in Fig. 3. As a result, we get a substitute circuit without the specified elements, which is presented in Fig. 4.

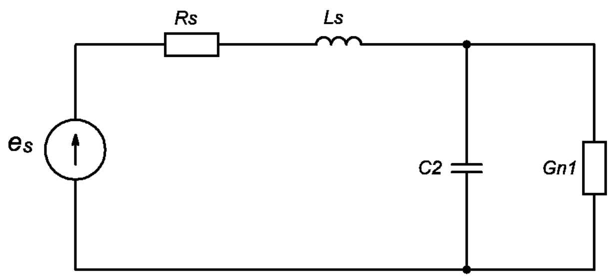

Fig. 4. Substitute circuit of the system with a compensator of the reactive component of the power transmission line

Stage 3. Now it is necessary to determine the capacity of the capacitor C_2, which is connected in parallel with the conductivity G_{n1} and must compensate for the reactive power of the inductance L_s of the power line. Next, let's turn the parallel circuit $G_{n1} - C_2$ into a series connection of the equivalent resistor R_3 and capacitor C_3 (Fig. 5).

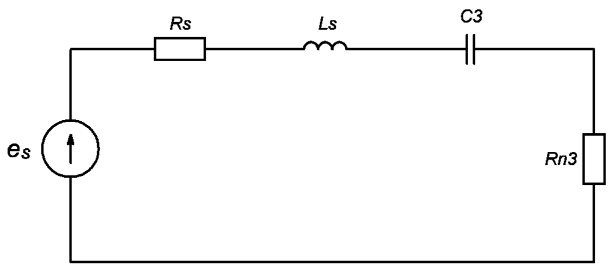

Fig. 5. Substitute circuit of the system at the stage of determining the capacity of the compensator for the power transmission line

We denote: $X_s = \omega L_s$, $Y_{C2} = \omega C_2$, $X_{C3} = 1/Y_{C3}$, $Y_{C3} = \omega C_3$. Then the parameters of the new load circuit will be obtained from the obvious relationships:

$$R_3 - jX_{C3} = \frac{1}{G_{n1} + jY_{C2}} = \frac{G_{n1} - jY_{C2}}{G_{n1}^2 + Y_{C2}^2}. \tag{5}$$

From here it is clear that

$$R_{n3} = \frac{G_{n1}}{G_{n1}^2 + Y_{C2}^2}; \tag{6}$$

$$X_{C3} = \frac{Y_{C2}}{G_{n1}^2 + Y_{C2}^2}. \tag{7}$$

In the circuit in Fig. 5 reactive elements are connected in series, and the conditions for the longitudinal compensation of the reactive power are to fulfill the condition $X_s = X_{C3}$, that is

$$X_S = Y_{C2}/(G_{n1}^2 + Y_{C2}^2), \tag{8}$$

which leads to the solution of the algebraic quadratic equation

$$Y_{C2}^2 - \frac{1}{X_S} Y_{C2} + G_{n1}^2 = 0. \tag{9}$$

From here we can determine the conductivity of the capacitor C_2:

$$Y_{C2} = \frac{1}{2X_S} \pm \sqrt{\frac{1}{4X_S^2} - G_{n1}^2}. \tag{10}$$

As can be seen from the obtained expression, the solution has two roots, from which, for the real case, the equation with the "minus" mark beforethe root should be chosen. The second value confirms the existence of two modes of full compensation of reactive power in the power supply system, which was indicated in previous works [14, 15], where the parameters of the second mode were obtained by a numerical method during optimization using the deformed polyhedron method. The second root corresponds to an overestimated compensation capacity and a significant increase in the current consumed from the source. Capacitance of capacitor C_2: $C_2 = Y_{02} / \omega$. Total capacity required for full compensation: $C_k = C_1 + C_2$.

Conditions for achieving the mode of full compensation. From expression (10), we can obtain the condition for achieving the full compensation mode, which consists in the fact that the radical

$$\frac{1}{4X_S^2} - G_{n1}^2 > 0. \tag{11}$$

This leads to the expression:

$$X_S < \frac{1}{2G_{n1}}. \tag{12}$$

Taking into account that

$$G_{n1} = \frac{R_n}{R_n^2 + X_n^2},$$

we obtain:

$$X_S < \frac{1}{2}(R_n + \frac{X_n}{R_n^2}). \tag{13}$$

Thus, **the method of using** the calculation relationships obtained above can be described as follows:

- We calculate the parallel load equivalent.
- Using the inductive component of the parallel equivalent, we find the capacity of the compensator, which compensates the purely reactive component of the load according to the relationship (4).
- We exclude the inductive component of the parallel equivalent of the load together with its capacitive compensator from the substitute circuit, since their total

conductivity is zero. We introduce into the substitute circuit the capacity C_2, which is designed to compensate for the reactive component of the power transmission line.

- According to relationipшз (13), we check the conditions for achieving full compensation of reactive power in the system.
- If full compensation can be achieved, we form equation (9) and solve it according to relationship (10), which allows us to determine the conductivity of compensator C_2.
- We calculate the capacity C_2 and the total capacity of the compensator, which ensures full compensation of the reactive power in the system.

Results of numerical analysis and modeling. Consider the generalized power supply system (Fig. 2) with the following parameters: $e_s(t) = 100\sin(\omega t)$, where $\omega = 100\pi$; $R_s = 3\ \Omega$; $L_s = 0.03$ H; $R_n = 7\ \Omega$; $L_n = 0.05$ H. Complex load resistance $Z_n = 7 + j15.708$.

The complex conductance of parallel equivalent of the load

$$G_{n1} - jY_{n1} = \frac{1}{7 + j15{,}708} = 0{,}0237 - j0{,}05311.$$

Conductivity of the capacitor C_1, which compensates for the reactance of the load $Y_{C1} = 0.053119$ S.

Capacitor C_1 capacity:

$$C_1 = \frac{Y_{C1}}{\omega} = \frac{0{,}05311}{100\pi} = 169{,}07\ \mu\text{F}.$$

Quadratic equation for finding conductivity Y_{C2}:

$$Y_{C2}^2 - 0{,}1061 \cdot Y_{C2} + 5{,}6024 \cdot 10^{-4} = 0,$$

where

$$Y_{C2} = 0{,}05305 - \sqrt{0{,}0028 - 5{,}24 \cdot 10^{-4}} = 0{,}0055728\ \text{S}.$$

The capacity of the capacitor C_2, which compensates for the inductance of the power transmission line:

$$C_2 = \frac{Y_{C2}}{100\pi} = 17{,}739\ \mu\text{F}.$$

Capacity that provides full compensation of reactive power in the system

$$C_k = C_1 + C_2 = 186{,}81\ \mu\text{F}.$$

According to the obtained results, the system was modeled for three options:

I – without compensating capacitor;

II – with capacity $C_k = C_1$, when partial compensation of only load reactivity is provided;

III – with capacity $C_k = C_1 + C_2$, which ensures full compensation of reactive power in the system.

For simulation, a visual model was created in the MATLAB/Simulink/SimPowerSystem system.

The configuration of the model actually repeats the circuit shown in Fig. 2, and therefore is not given. The complex values of the voltage on the capacitor $\dot{U}_C$, that is, the voltage on the load, is measured; as well as power source current $\dot{I}_S$; capacitor's C_k current $\dot{I}_C$; current $\dot{I}_{Zn}$ through the load. The simulation results are given in Table 1.

Table 1

Simulation results

Parameters	Option I	Option II	Option III
C_k	0	C_1	$C_1 + C_2$
$\dot{U}_C$	63,8∠–2,32°	91,41∠–11,77°	95,57∠–13,25°
$\dot{I}_S$	3,7∠–68,3°	2,16∠–11,77°	2,32∠0°
$\dot{I}_C$	0	4,86∠78,23°	5,61∠76,75°
$\dot{I}_{Zn}$	3,7∠–68,3°	5,33∠–77,75°	5,56∠–79,23°

Analyzing the given results, it is worth noting that in the absence of a compensating capacitor, the mode is characterized by an extremely low level of voltage supplied to the load. A relatively large current is consumed from the source, which creates a sufficiently large voltage drop on the complex resistance of the power transmission line, the amplitude of which reaches more than 30 % of the voltage of the source itself. Calculation of the value of the power factor gives a very low value of cos(68,30°) = 0.369. Application of partial compensation at $C_k = C_1$ fully compensates the reactive power of the load. This is evidenced by the same phase shifts of the load voltage $\dot{U}_C$ and current $\dot{I}_S$, i.e. the load behaves like an active resistor in conjunction with the capacitor C_1. This, in turn, confirms the effectiveness of the substitute circuit shown in Fig. 4 at $C_2 = 0$. Indeed, by dividing the current $\dot{I}_S$ by the voltage $\dot{U}_C$, we obtain the conductivity of the load equivalent

$$G_{eq2} = \frac{2{,}16\angle -11{,}77°}{91{,}41\angle -11{,}77°} = 0{,}02363\ \Omega^{-1}.$$

which coincides with G_{n1} of the substitute circuit in Fig. 4. Equivalent resistance $R_{n1} = 1 / G_{n1} = 42.319\ \Omega$. Without compensation, the load module was

$$|Z_n| = \sqrt{7^2 + 15{,}708^2} = 17{,}971\ \Omega.$$

Thus, the connection of the capacitor C_1, which compensates for the reactance of the load, can be interpreted as a significant increase in the equivalent resistance of the load. Due to this, the current consumed from the source is reduced. At the same time, the share of the source voltage, which goes directly to the load nodes, increases. Although the voltage drop on the power transmission line is reduced by almost three times and is now about 10 % of the source voltage, the voltage at the load still does not reach 5 % of the permissible deviation. In the third option, $C_k = C_1 + C_2$, and here full compensation of the reactive power in the system is achieved. This is evidenced by the coincidence of the phase of the current $\dot{I}_S$ of the source with the phase of its voltage $e_s(t)$. Thanks to the additional compensation of the inductance of the power transmission line, the load voltage $\dot{U}_C$ increases and reaches 5 % of the permissible deviation from the source voltage. The current consumed from the source increases slightly. This can be explained by the substitute circuit shown in Fig. 5, if we take into account that the sum of the reactances of the inductance L_s and the capacitor C_3 is zero. Therefore, these elements can be removed from the circuit by replacing them with a short-circuited conductor. We get a simple substitute circuit with serial connection of resistors R_s and R_{n3}. Let's calculate the resistance of the last resistor according to (6):

$$R_{n3} = \frac{G_{n1}}{G_{n1}^2 + Y_{C2}^2} = \frac{0,0237}{0,0237^2 + 0,0055728^2} = 39,983\ \Omega.$$

As can be seen, the resistance R_{n3} slightly decreases compared to R_{n1}. Current $\dot{I}_S$ calculated taking into account R_s and R_{n3}:

$$\dot{I}_S = \frac{100}{3 + 39,9834} = 2,326\ \text{A},$$

which coincides with the simulation results in Table 1.

The voltage on the load is calculated as the geometric sum of the voltages on R_{n3} and C_3:

$$U_{n3} = \left[(I_s R_{n3})^2 + (\frac{1}{\omega C_3} \cdot I_s)^2 \right]^{1/2} = 95,59\ \text{V},$$

which also coincides with the simulation results.

A visual model in the MATLAB/SimPowerSystem system was used for modeling in time space (Fig. 6). Virtual devices allow to determine the amplitudes of currents and voltages, as well as active and reactive power on system elements.

Shown in Fig. 6 results correspond to the mode of full compensation. It can be seen here that the source gives only active power P_e = 116.2 W, active load power is P_n = 108.1 W, active losses on the power transmission line and generator resistance is P_s = 8.102 W. The reactive power associated with the power source is zero, and therefore the power factor cosφ = 1. The efficiency of the system is η = 108.1 / 116.2 = 0.93. At the same time, for the uncompensated mode, these values are P_e = 68.34 W, P_n = 47.84 W, P_s = 20.5 W, η =47.84 / 68.34 = 0.7. The reactive power given by the source in this case is Q_e = 171.8 VAr, which causes a low value of the power factor cosφ = 0.37. These results clearly show in favor of the full compensation mode, thanks to which the load consumes a voltage close to the nominal one, which in turn ensures the appropriate level of power consumption, losses on the power transmission line are reduced by 2.5 times, and the efficiency is increased by 23 %. Thus, when full compensation is implemented, the energy indicators of the power supply system are significantly increased and normal power supply of the load is ensured, which in the absence of compensation overloads the network and thereby unacceptably lowers the voltage at the point of connection of this load.

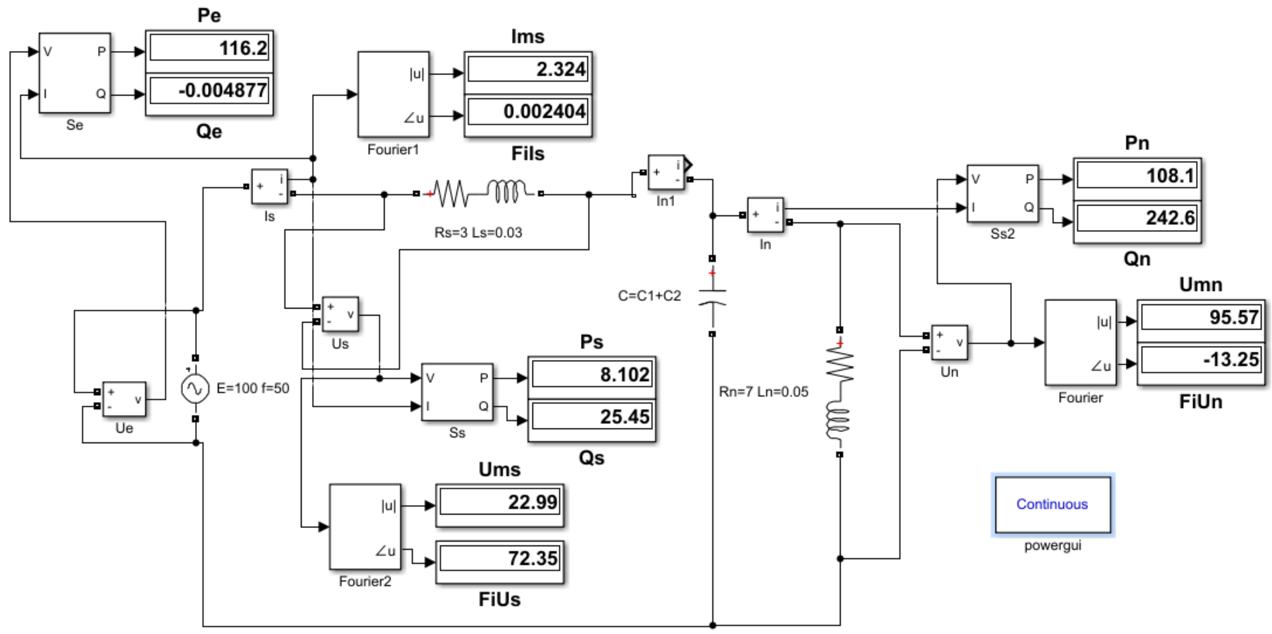

Fig. 6. Visual model of the system for verification of the full compensation mode

Conclusions.

1. An analytical method for determining the conditions for achieving full compensation of reactive power in a generalized power supply system is proposed, which is based on equivalent transformations of the topology of the power supply system and allows not to apply complex methods of solving nonlinear equations by iterative and optimization methods.
2. On the basis of the proposed method, an analytical technique for calculating the parameters of the compensating device and the mode parameters of the system was developed, and its verification was performed, which confirmed the coincidence of the obtained results with known examples of the implementation of full compensation of reactive power.
3. It follows from the conducted analysis that the generally accepted partial compensation of the load reactance may not ensure a proper increase in the load voltage, at the same time, the use of full reactive power compensation ensures a further increase in the load voltage.
4. It is shown that the processes of increasing the load voltage and decreasing the source current can be interpreted as an increase in the equivalent resistance of the load.
5. The proposed method and calculation methodology based on it have the prospect of being applied in the analysis of reactive power compensation processes in electrical networks with many loads and several sources of electricity supply.

6. The results of modeling the mode in the system on the model compiled in the MATLAB/Simulink/SimPowerSysten package with the specified initial parameters and the found parameters of the compensator show an absolute coincidence with the results of mode calculations obtained using the developed methodology.

Conflict of interest. The authors declare that they have no conflicts of interest.

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