Представлено дослідження режимів в однофазній узагальненій системі електропостачання в аспекті підвищення енергетичних показників в системі шляхом компенсації реактивної потужності. Розглянуті три тестових варіанта системи електропостачання з різними співвідношеннями комплексних опорів навантаження та лінії електропередачі. Показані недоліки традиційного методу розрахунку параметрів компенсуючого пристрою, які забезпечують часткову компенсацію реактивної потужності, що споживається лише навантаженням. Аналіз режиму часткової компенсації свідчить про те, що зі збільшенням реактивності лінії електропередачі погіршуються енергетичні показники, які вдається отримати в результаті компенсації реактивної потужності. З застосуванням пошукової оптимізації показано, що для повної компенсації потрібне збільшення ємності компенсатора. Метод пошукової оптимізації реалізований в пакеті програм комп'ютерної математики MathCAD за допомогою вирішального блоку given-find. Для цього використовуються рівняння математичної моделі системи електропостачання на основі компонентних і топологічних рівнянь. В якості додаткових умов використані співвідношення, що визначають повну компенсацію реактивної потужності живильного джерела, а також умови фізичної можливості бути реалізованим структури компенсуючого пристрою Перемінними оптимізації є параметри досліджуваного режиму і параметри компенсуючого пристрою. Представлені фрагменти текстів програм з числовими результатами розв'язань, а також порівняльні таблиці результатів аналізу і оптимізації режимів компенсації реактивної потужності в досліджуваних системах електропостачання для всіх варіантів їх параметрів. Дані кількісні оцінки величини додаткової ємності, яка обчислюється виходячи з умови компенсації нею реактивної потужності в лінії електропередачі. Дослідження, що проведені в роботі, показали, що при збільшенні реактивного опору лінії електропередачі повна компенсація не може бути досягнута із застосуванням поперечної компенсації і цьому явищу дана фізична трактовка. Вона полягає в тому, що напруга на компенсуючому поперечному конденсаторі зменшується швидше, ніж зростає компенсована ним реактивна потужність лінії електропередач. Показано, що в останньому випадку повна компенсація реактивної потужності все ж може бути досягнута застосуванням комбінованої поздовжньо-поперечної компенсації

Ключові слова: система електропостачання, реактивна потужність, режим компенсації, лінія електропередачі, компенсуючий пристрій

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ANALYSIS AND OPTIMIZATION OF THE REACTIVE POWER COMPENSATION MODES IN A POWER SUPPLY SYSTEM

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1. Introduction

Improving energy performance in power supply systems is an important direction in the theory and practice of power generation industry. In particular, the improvement of the conditions for the electricity transmission along the path "source – transmission line – load" is accompanied by a decrease in currents through the transmission line. This in turn

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contributes to the reduction of losses in the transmission of electricity, and, consequently, increases the efficiency, determining the energy efficiency of the power supply system in general. One of the main reserves for improving the energy performance of power supply systems is the compensation of reactive power in the system. The relevance of the task to accurately define the conditions for full compensation of reactive power is predetermined by the possibility of maximum unloading of electric power networks by installing static compensators and fine-tuning their parameters. The importance of this problem's correct solution is enhanced as the intelligent processes related to electrical networks are developed by introducing modern microprocessor equipment to the control systems over the processes of power supply and power consumption.

2. Literature review and problem statement

The issues of reactive power compensation are covered in a series of papers [1–6]. The authors of [1] considered general considerations for ensuring the compensation of reactive power load, but bringing the power factor to the maximum single value is not provided. Reactive power of higher harmonics is investigated in [2], while the struggle for increasing energy indicators is carried out only by suppressing higher harmonics, that is, the impact is carried out only on the current distortion factor, and the shift factor is not considered. In [3], the issues of reactive power compensation are considered mainly from the point of view of its regulation by electronic device, which is characterized by a significant complication of compensating devices that require the use of expensive power semiconductor devices and rather complex intelligent control systems. In addition, the signals for the formation of correction currents in known systems are removed from the load terminal, which does not ensure the complete suppression of reactive power in the system. Indeed, the voltages at the attachment points of the load differ from the voltages of the energy sources, since part of the voltage falls on the resistances of the transmission lines. These resistances can generally reach significant values, taking into consideration the length of the transmission line and a significant number of voltage conversions by transformers in the transmission of electricity from the energy source to the consumer. The issues of placing compensating devices at industrial enterprises are set forth in [4], and the task of complete suppression of reactive power is not posed and is not solved. In [5], scientists gave an example of calculating compensating devices when powering an active-inductive load from a synchronous generator with given parameters. Here, however, due to the lack of a systematic approach, the solution of the problem is also limited to incomplete compensation of reactive power in the system. Thus, the problem of full compensation of reactive power is also not solved. In addition, with the parameters of the synchronous generator adopted in this work, full compensation of reactive power is fundamentally impossible when using a device for shunt compensation of reactive power. The issues of voltage control in power transmission systems by regulating reactive power flows are highlighted in [6], but the case of combined reactive power compensation, capable of fully compensating reactive power, has not been considered. In the periodicals of recent years, the relevance of optimizing reactive power compensation processes is also not reduced. Thus, the authors of [7] justified the need for continuous monitoring of reactive power and improving the accuracy of its compensation processes. The importance of reactive power compensation in the conditions of a local isolated power supply system is indicated in [8]. And in [9], elements of optimizing the processes of reactive power compensation in a system with a low-power hydrogenerator are given, which also indicates the relevance of the issues considered in this article. It should be noted in the design plan that in most cases of generalization, the load in the power supply systems in the design plan of industrial and public utilities is actively inductive in nature. Therefore, the method of reactive power compensation by connecting parallel to the load of capacitor banks [1–3] has received practical application. For generalized calculations when using group compensation of reactive power, the calculation of the reactive power amount is usually applied, the compensation of which should be provided by capacitors to achieve a power factor from the initial value of cosφ1 to the final value of cosφ2. This corresponds to known expression [4]

$$\Delta Q_C = P(tg\varphi_1 - tg\varphi_2), \tag{1}$$

where ΔQ_C is the reactive power, compensated by a battery of capacitors; P is the active power consumed by the load in which compensation is performed; φ1, φ2 are the initial and final angles, reflecting the current shift relative to the supply voltage in the absence of compensation and in its presence.

Further, the received capacitance can be determined from the obtained reactive power difference and the rated voltage across the load. When connecting compensating capacitors in a triangle the capacity of each battery connected to the line voltage U_n, is determined from the following formula:

$$C = \frac{\Delta Q_C}{3\omega U_{\text{n}}^2}, \tag{2}$$

where ω is the circular frequency of supply voltage.

Another approach used to solve a specific problem of reactive power compensation in a system powered by a synchronous generator [5] is to find a capacitance value that is able to compensate for the reactive component of the active-inductive load conductance. This approach is actually equivalent to that adopted in the power industry and uses expressions (1) and (2). Meanwhile, with both approaches to determining the parameters of a reactive power compensator, only the parameters of the load are taken into consideration, and the reactivity of transmission lines remains uncompensated. Thus, traditional approaches do not solve the problem of full reactive power compensation in the power supply system. This means that this provides only partial compensation of reactive power in the system, and, therefore, there is a reserve to achieve a more efficient mode of compensation of reactive power in the system. It should also be noted that the approaches described assume a complete symmetry of the three-phase system, and, therefore, are unsuitable for accurate determination of capacitors capacitances that ensure the balancing of currents and voltages in the system. The latter is important from the point of view of the need for uniform loading of the supply system phases, as well as ensuring symmetrical modes for the supply transformers [6, 10]. In terms of the development of intelligent electric power systems equipped with information systems for monitoring all parts of the power supply system and operational control in automatic mode, the issues of ensuring full compensation of reactive power become extremely relevant. With such mode optimization, it is possible to achieve a significant increase in the energy efficiency of the electrical system in general. And in this regard, the development of approaches and methods for analyzing and optimizing the modes of the power supply system in order to determine the parameters of reactive power compensators, ensuring full compensation of reactive power, should be a relevant and promising task.

3. The aim and objectives of the study

The aim of this work is to analyze and optimize reactive power compensation modes, taking into consideration the possible ratios of load reactors and power transmission lines and bring the modes to full compensation of reactive power in the system. Achieving this goal will provide an opportunity to use the reserve of reducing reactive power and improve the energy performance of the power supply system in general.

To achieve this goal, the following tasks were set:

– to construct mathematical models of the power supply system using search engine optimization to determine the operating parameters of the system and the parameters of compensating devices;

– to carry out analysis and optimization of reactive power compensation modes with the help of mathematical models for different ratios between the complex resistance of the load and the power line and compare the results obtained;

– identify the conditions under which shunt compensation is unable to provide full compensation of reactive power, give this phenomenon a physical justification and solve the problem of full compensation using a combined reactive power compensator.

4. Constructing a mathematical model for the analysis and optimization of power supply system modes

We will consider the generalized power supply system in a single-phase variant (Fig. 1), which is acceptable in the case of three-phase power supply system symmetry with towards to one of the phases.

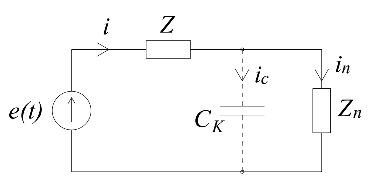

Fig. 1. Generalized power supply system with a reactive power compensator

In this system e(t) is the sinusoidal power supply; z_n is the load impedance of active-inductive nature: $z_n=R_n+jx_n z$ is the impedance, which includes power lines and the internal resistance of an electrical energy real generator: $z=r+jx$. Condenser C_K is used as a compensator for reactive power, simulating load resistance. Thus, the recommended connection points of the compensating device are load connection clamps, which means the implementation of lateral reactive power compensation.

The complete compensation mode implies such a mode in which the sources of supplying sinusoidal voltages give the sinusoidal currents to the power supply system, coinciding in phase with the generated sinusoidal voltages. It is obvious that in the full compensation mode, the sources give only active power, which corresponds to the maximum possible single value of the power factor. In the case of a linear load under consideration, the power factor [1–3] is determined only by the angle of current shift relative to voltage. Accurate determination of the compensator parameters, providing full compensation of reactive power, is a non-linear problem. Its exact solution is possible only with the use of search engine optimization methods [11–13]. The solution of the problem is then carried out in the computer mathematics system Mathcad for the following normalized parameters of the generalized power supply system scheme: $z_n=0.7+j\omega 0.005$; $z=0.1+j\omega 0.001$; $e(t)=100$. The voltage of 100 V of the supply source is convenient to accept for calculations, since the percentage component of any voltages in the system is immediately visible relative to the reference voltage source. Any voltage of a real system can be easily reduced to such a value by dividing the actual voltage of the source by the corresponding base voltage. The text of the program for analyzing the modes of the power supply system that provides search engine optimization using Mathcad is shown in Fig. 2.

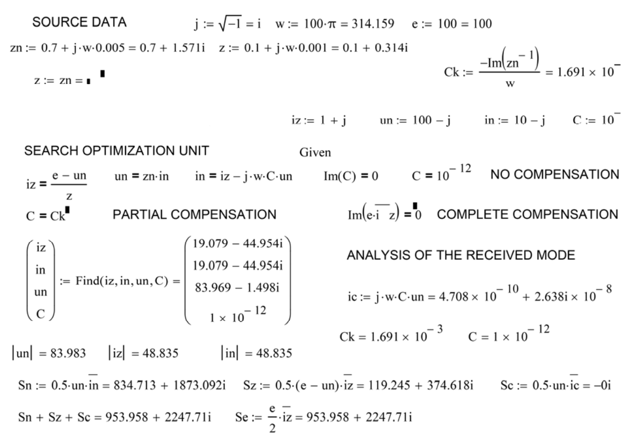

Fig. 2. Mathcad-based program that provides search engine optimization for the original mode without compensation

In the "Source data" unit, the circular frequency and voltage amplitude of the power supply voltage are set. After setting the load impedance z_n the capacitance of the capacitor is calculated, which compensates for the load reactivity, which is carried out according to formula

$$C_k = \frac{\mathrm{Im}(z_n^{-1})}{\omega} \quad (3)$$

based on that the conductivity of the capacitor must compensate for the reactive component of the load conductivity. Next, we set the total impedance z, which includes the internal resistance of the transmission line. The blocked operator under the comment (*equality of leverages*) allows an increase in the resistance z up to value z_n, which will be used for the further research.

In the unit "Initial values for optimization parameters" we assign initial values for current i_z in a power line, voltage u_n on the load, current i_n in the load, and the capacitance of compensating capacitor C. The specified variables create a vector of optimization variables whose values are determined form the subsequent search optimization based on the optimization conditions. The search optimization unit is implemented by a pair of given-find operators that provide search optimization under conditions that are specified inside this unit. Conditions are written in the form of equations recorded using a special symbol "=" of logical equality. The first three conditions in the unit assign equations of the mathematical model of a power supply system based on the equations in line with Ohm and Kirchhoff's laws. The following equation provides for the found value of capacitance of the compensating capacitor in the form of a real number. Of the following three conditions, supplied with comments "Without Compensation", "Partial Compensation", "Full Compensation", only one condition must be unblocked, which corresponds to the chosen variant of the mode under consideration.

5. Analysis and optimization of the mode at a small magnitude for the power line complex resistance

Fig. 2 shows the unlocked operator $C=10^{-12}$, which *a priori* provides for a very small value of capacitance C of the capacitor, that is, in fact, the capacitor is excluded from the power supply system. In this case, the original mode is investigated in the absence of a compensating device. When unblocking the "Partial Compensation" line, a capacitance value equal to the capacitance C_k, is compensated, compensating only the load reactivity and calculated above in the section "Source data". If the condition is unlocked under the comment "full compensation", then the following condition is included

$$\mathrm{Im}(e \cdot i^{*}) = 0. \tag{4}$$

Under this condition, an optimization process is provided in which the target function assumes a value proportional to the reactive power of the source, and the optimization variables accept the currents in the system and the capacitance value of the compensating device. At the same time, in order to perform physical realizability, the capacity value is limited to a real value. Condition (4) ensures that the reactive power supplied by the source is zero and corresponds to the case of full compensation. The determination of the optimal values of the optimization variables is provided by the operator Find (i_z, i_n, u_n, C), where the order of enumeration of the optimization variables corresponds to the order of issuing the optimal values of the variables in the solution vector. The optimal values found are immediately assigned to the variables themselves, listed in the vector in the left part of the Find operator.

In the unit "Analysis of the received mode" one finds a current i_c through a compensating capacitor. For comparison, the values of capacitances C and C_k are given, which will be different for the case of full compensation. The following are the amplitude value for voltage u_n under the load, current i_z through the power line, and current i_n through the load.

Further, the total powers are calculated: S_n – consumed by the load, S_z – consumed by the power line, S_c – consumed by the compensating capacitor, S_e – given off by the source of electric power. Summation of the passive elements S_n+S_z+S_c and comparison of this sum with the power S_e of the active element makes it possible to check the power balance [1–3]. The analysis of the original uncompensated mode, shown in Fig. 2 in the last section of the worksheet, shows that 16 % of the voltage falls on the transmission line, which means that the load is working at a reduced voltage U_n, and, consequently, the shortage in load power is S_n=834+j1,873. At the same time, a load current with an amplitude of 48.8 A flows through the power line, which causes a significant level of active power loss in the power line (Re(S_z)=119.245 W). It should also be noted that the source is loaded with a significant reactive power (Im(S_e)=2,247 VAr).

Fig. 3 shows a fragment of the program corresponding to the partial compensation option.

It is clear from the solution that $C=C_k$ is met. The voltage on the load increased to 97.4 % of the power supply, due to which the power consumed by the load also increased (S_n=1,123+j2,521). It has been achieved through to a decrease in the current through the power line (i_z=23.00), and the losses decreased (Re(S_z)=26.59). At the same time, the reactive power in the system is not fully compensated, since the source of electricity gives off reactive power Im(S_e)=83.5 VAr.

Fig. 4 shows a fragment of the program that provides an analysis of the mode of reactive power full compensation.

$$\begin{pmatrix} iz \\ in \\ un \\ C \end{pmatrix} := \mathrm{Find}(iz, in, un, C) = \begin{pmatrix} 23.001 - 1.671i \\ 19.252 - 53.284i \\ 97.175 - 7.059i \\ 1.691 \times 10^{-3} \end{pmatrix}$$

ANALYSIS OF THE RECEIVED MODE

$$ic := j \cdot w \cdot C \cdot un = 3.749 + 51.614i$$

$$Ck = 1.691 \times 10^{-3} \qquad C = 1.6907 \times 10^{-3}$$

$$|un| = 97.431 \qquad |iz| = 23.061 \qquad |in| = 56.656$$

$$Sn := 0.5 \cdot un \cdot \overline{in} = 1123.447 + 2521.01i \qquad Sz := 0.5 \cdot (e - un) \cdot \overline{iz} = 26.591 + 83.539i \qquad Sc := 0.5 \cdot un \cdot \overline{ic} = -2521.01i$$

$$Sn + Sz + Sc = 1150.039 + 83.539i \qquad Se := \frac{e}{2} \cdot \overline{iz} = 1150.039 + 83.539i$$

Fig. 3. Fragment of the program corresponding to partial compensation

$$\begin{pmatrix} iz \\ in \\ un \\ C \end{pmatrix} := \mathrm{Find}(iz, in, un, C) = \begin{pmatrix} 23.248 \\ 19.24 - 53.608i \\ 97.675 - 7.304i \\ 1.747 \times 10^{-3} \end{pmatrix}$$

ANALYSIS OF THE RECEIVED MODE

$$ic := j \cdot w \cdot C \cdot un = 4.009 + 53.608i$$

$$Ck = 1.691 \times 10^{-3} \qquad C = 1.747 \times 10^{-3}$$

$$|un| = 97.948 \qquad |iz| = 23.248 \qquad |in| = 56.956$$

$$Sn := 0.5 \cdot un \cdot \overline{in} = 1135.397 + 2547.824i \qquad Sz := 0.5 \cdot (e - un) \cdot \overline{iz} = 27.024 + 84.9i \qquad Sc := 0.5 \cdot un \cdot \overline{ic} = -2632.724i$$

$$Sn + Sz + Sc = 1162.421 \qquad Se := \frac{e}{2} \cdot \overline{iz} = 1162.421$$

Fig. 4. Fragment of the program corresponding to full compensation

Here, the operator $I_m = (e \cdot i_z^{*}) = 0,$ is unblocked, due to which the optimization ensures that the solution is found under the condition that the imaginary part of the total power given by the source is zero. In this case, the voltage on the load reached its higher value ($|U_n|$=97.431 V). The capacitance of the compensating capacitor increased to C=1,747 μF, which is slightly higher than the capacitance value C_k=1,691 μF, necessary to compensate for the load reactivity. Due to the increase in voltage at the load, and, consequently, on the compensating capacitor itself, as well as because of the increase in the capacitance of the capacitor, the currents consumed by the capacitor and the load increase, which leads to an increase in the current in the transmission line to the value $|i_z|$=23.248. The power source, as it was set during optimization, gives an active power of 1,162.421 W at zero reactive power. The summary of Table 1 allows us to compare the operating parameters of the system under consideration for all three modes.

Table 1

Comparison of mode parameters

Parameter	Without compensation	Partial compensation	Full compensation
Capacity of the compensating condenser	10^{-12}	$1.691 \cdot 10^{-3}$	$1.747 \cdot 10^{-3}$
Load current amplitude, i_n	48.835	56.656	56.956
Power Line Current Amplitude, i_z	48.835	23.061	23.248
Load voltage amplitude, u_n	83.983	97.431	97.948
Total power consumed by the load, S_n	835+*j*1,873	1,123+*j*2,521	1,135+*j*2,547
Full power consumed by power line, S_z	19.25+*j*374.6	26.59+*j*83.4	27.02+*j*84.9
The total power consumed by the capacitor, S_C	–*j*0	–*j*2,521	–*j*2,632
Total power delivered by source, S_e	953.9+*j*2,247.2	1,150+*j*83.54	1,162.4+*j*0

Comparing the results of computer experiments, we can conclude that the minimum loss in the transmission line is provided by the partial compensation mode; however, there is a reduced voltage on the load in comparison with the full compensation mode. In both cases of reactive power compensation, the current in the transmission line is halved compared with the mode in the absence of compensation. The increase in the capacitance of the compensating capacitor in the full compensation mode can be physically explained by the fact that the additional reactive power is used to compensate for the reactive power of the transmission line. The small value of the increment in the capacitance of the compensating capacitor can be explained by the small inductance of the power line. Consider how the parameters of the system and the system itself will affect the increase in the integrated resistance of the transmission line.

In case of equality of power transmission and load shoulders:

$$z = z_n = 0{,}7 + j\omega 0{,}005.$$

For this purpose, unblock the corresponding operator in the “Source data” section. The mode without compensation of this test circuit is shown in Fig. 5, where one can see that the voltage on the load is exactly half the supply voltage.

Connecting the capacitance C_k, which provides partial compensation (the program in Fig. 6), allows us to increase the load voltage to 81.8 V.

Under the full compensation mode (program in Fig. 7), the voltage on the load allows another 10 % increase in the voltage on the load and bring it to 91.3 V.

$$\begin{pmatrix} iz \\ in \\ un \\ C \end{pmatrix} := \mathrm{Find}(iz, in, un, C) = \begin{pmatrix} 11.835 - 26.557i \\ 11.835 - 26.557i \\ 50 - 5.498i \times 10^{-9} \\ 1 \times 10^{-12} \end{pmatrix}$$

ANALYSIS OF THE RECEIVED MODE

$ic := j \cdot w \cdot C \cdot un = 1.571i \times 10^{-8}$

$Ck = 1.691 \times 10^{-3}$ $\quad C = 1 \times 10^{-12}$

$|un| = 50.000$ $\quad |iz| = 29.075$ $\quad |in| = 29.075$

$Sn := 0.5 \cdot un \cdot \overline{in} = 295.868 + 663.926i$ $\quad Sz := 0.5 \cdot (e - un) \cdot \overline{iz} = 295.868 + 663.926i$ $\quad Sc := 0.5 \cdot un \cdot \overline{ic} = -0i$

$Sn + Sz + Sc = 591.736 + 1327.852i$ $\quad Se := \frac{e}{2} \cdot \overline{iz} = 591.736 + 1327.852i$

Fig. 5. Program for calculating the mode without compensation with equal shoulders

$$\begin{pmatrix} iz \\ in \\ un \\ C \end{pmatrix} := \mathrm{Find}(iz, in, un, C) = \begin{pmatrix} 18.43 - 5.878i \\ 5.239 - 47.236i \\ 77.865 - 24.835i \\ 1.691 \times 10^{-3} \end{pmatrix}$$

ANALYSIS OF THE RECEIVED MODE

$ic := j \cdot w \cdot C \cdot un = 13.191 + 41.357i$

$Ck = 1.691 \times 10^{-3}$ $\quad C = 1.6907 \times 10^{-3}$

$|un| = 81.730$ $\quad |iz| = 19.345$ $\quad |in| = 47.525$

$Sn := 0.5 \cdot un \cdot \overline{in} = 790.531 + 1773.949i$ $\quad Sz := 0.5 \cdot (e - un) \cdot \overline{iz} = 130.98 + 293.918i$ $\quad Sc := 0.5 \cdot un \cdot \overline{ic} = -1773.949i$

$Sn + Sz + Sc = 921.512 + 293.918i$ $\quad Se := \frac{e}{2} \cdot \overline{iz} = 921.512 + 293.918i$

Fig. 6. Calculation of the mode with partial compensation with equal shoulders

$$\begin{pmatrix} iz \\ in \\ un \\ C \end{pmatrix} := \mathrm{Find}(iz, in, un, C) = \begin{pmatrix} 23.669 \\ -53.114i \\ 83.431 - 37.18i \\ 2.026 \times 10^{-3} \end{pmatrix}$$

ANALYSIS OF THE RECEIVED MODE

$ic := j \cdot w \cdot C \cdot un = 23.669 + 53.114i$

$Ck = 1.691 \times 10^{-3}$ $\quad C = 2.0264 \times 10^{-3}$

$|un| = 91.341$ $\quad |iz| = 23.669$ $\quad |in| = 53.114$

$Sn := 0.5 \cdot un \cdot \overline{in} = 987.387 + 2215.691i$ $\quad Sz := 0.5 \cdot (e - un) \cdot \overline{iz} = 196.085 + 440.013i$ $\quad Sc := 0.5 \cdot un \cdot \overline{ic} = -2655.704i$

$Sn + Sz + Sc = 1183.472$ $\quad Se := \frac{e}{2} \cdot \overline{iz} = 1183.472$

Fig. 7. Calculation of the full compensation mode with equal shoulders

Summary data for the three modes of the second test circuit is included in Table 2.

Table 2

Mode parameters with equal shoulders

Parameter	Without compensation	Partial compensation	Full compensation
Capacity of the compensating condenser	0	1691 μF	2026.4 μF
Load current amplitude, i_n	29.075	47.525	53.114
Power line current amplitude, i_z	29.075	19.345	23.669
Load voltage amplitude, u_n	50.0	81.73	91.341
Total power consumed by the load, S_n	296+j664	791+j1,774	987+j2,216
Full power consumed by power line, S_z	296+j664	131+j294	196+j440
The total power consumed by the capacitor, S_C	0	–j1,774	–j2,656
Total power delivered by source, S_e	592+j1,328	922+j294	1,183+j0

Table 2 shows that the full compensation mode provides maximum power at the load due to a significant increase in the voltage amplitude at the load.

The value of capacitance C, which provides full compensation of reactive power, for the second test system, is even more different from the value of C_k, which provides compensation for load reactivity. This increase can be interpreted as an additional ΔC, which provides additional compensation for the reactivity of the load line. This separation leads to the equivalent circuit shown in Fig. 8.

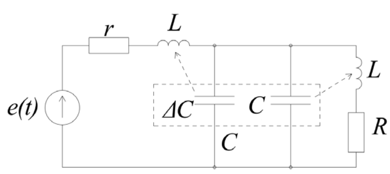

Fig. 8. Equivalent circuit with a dedicated capacitor, taking into consideration the power line

Here, the capacitance of the compensating device C is conventionally divided into C_k, which compensates for load reactivity, and on ΔC, which compensates for the reactivity of the transmission line. It is impossible to directly calculate the additional capacitance of ΔC since it is necessary to know the exact value of the total voltage on the load and on the compensating capacitor directly in the mode of full compensation of reactive power. This can be done by an additional fragment of the program shown in Fig. 9, *a*, and for the first test version of the system.

Here the search engine optimization unit forms a solution for the previously calculated full compensation mode (Fig. 4). When the values of the voltage on the capacitors C_k and ΔC (Fig. 8) are found, the value $\Delta C = DC$, which provides the same reactive power consumption by the capacitor ΔC, which consumes inductive resistance Im(z) of the power supply line, is calculated. To check at the end of the posted operator, showing the difference $C - C_k$, which is exactly equal to the additional capacitance of ΔC.

Share control PM in z:

$$iDC := 1 + j \qquad DC := 10^{-6}$$

Given

$$iDC = j \cdot w \cdot DC \cdot un$$

$$Im(Sz) = -Im\left(0.5 \cdot un\,\overline{iDC}\right)$$

$$Im(DC) = 0$$

$$\begin{pmatrix} DC \\ iDC \end{pmatrix} := Find(DC, iDC) = \begin{pmatrix} 5.63374 \times 10^{-5} \\ 0.12927 + 1.72875i \end{pmatrix}$$

$$C - Ck = 5.63374 \times 10^{-5}$$

a

Share control PM in z:

$$iDC := 1 + j \qquad DC := 10^{-6}$$

Given

$$iDC = j \cdot w \cdot DC \cdot un$$

$$Im(Sz) = -Im\left(0.5 \cdot un\,\overline{iDC}\right)$$

$$Im(DC) = 0$$

$$\begin{pmatrix} DC \\ iDC \end{pmatrix} := Find(DC, iDC) = \begin{pmatrix} 3.3575 \times 10^{-4} \\ 3.92169 + 8.80026i \end{pmatrix}$$

$$C - Ck = 3.3575 \times 10^{-4}$$

b

Fig. 9. Programs that calculate the values of additional capacities: *a* – for the first variant of the test circuit, *b* – for the second variant of the test circuit

In Fig. 9, *b*, a similar program fragment is shown, which calculates the additional capacity ΔC for the second test system, for which the calculation of the full reactive power compensation mode is presented in Fig. 7. In this case, determined from the condition of equality of the reactive powers of the transmission line inductance and the additional capacitor ΔC, the capacitance of the latter is exactly equal to the difference between the capacitances C and C_k, which respectively provide full and partial compensation.

The impact of the compensator C, connected in parallel to the load and thus implementing the so-called shunt compensation, is not always able to bring the power supply system to full compensation. As a confirmation, we consider a generalized power supply system with the parameters specified when solving the problem of reactive power compensation in [5].

6. Analysis and optimization of the mode with a significant value of the power line complex resistance

Here, the parameters of the system are borrowed from [5], where the system was fed from a synchronous generator with a power of S_G=15 MVA and a voltage of U_n=6,300 V. The internal resistance of the generator is taken to be Z_G=0.066+j3.2. When the resistance of the power line is Ze=0.11+j0.063. The load resistance is assumed to be Z_n=2.015+j1.511. Then the shoulder resistance of the power line will be obtained by summing the complex resistances of the generator and the power line: $Z = Z_G + Z_e = 0.176 + j3.263$.

Attention is drawn to the relatively large value of the inductive resistance of the X_G generator compared with the inductive load resistance X_n. We will estimate the base resistance of the synchronous generator

$$z_0=\frac{U_n^2}{S}=\frac{6{,}3^2}{15}=2{,}646. \quad (5)$$

Relative value of a synchronous generator inductive resistance is

$$x^*=\frac{x_G}{z_0}=\frac{3{,}2}{2{,}646}=1{,}209, \quad (6)$$

which is much more in comparison with the range X^*= =0,08÷0,3 for synchronous turbo and hydrogenerators [10]. Even the upper limit estimate X^*=0,3 leads to the maximum permissible generator resistance

$$X_G=0.3\cdot 3.646=0.794 \text{ Ohm}. \quad (7)$$

Thus, the excess of the parameter over the limit value is 3.2/0.794=4. Note that in [5] the choice of such an inductive impedance of a synchronous generator is not justified by anything. In addition, in [5], it is *a priori* assumed that energy is transmitted through the line with a 5 % voltage loss, which is not true for the accepted parameters. Fig. 10 shows the results of the initial mode system analysis with the parameters adopted in [5].

The source voltage is then considered normalized and amounts to 100 V. As can be seen from the solution, the voltage at the load is 47.9 V, which is much less than the expected 95 V in [5]. Due to the reduced voltage, due to the high resistance of the power line, the power developed at the load is only a quarter of the expected power, which does not represent the nominal mode in the power supply system.

The mode of partial compensation of reactive power is carried out by connecting a capacitor C_k=758.2 μF, compensating only the reactive power of the load. The worksheet corresponding to this mode with the program is shown in Fig. 11.

Partial compensation made it possible to increase the voltage at the load to 67.6 V, that is, to 2/3 of the nominal, which leads to the development of the power at the load, which is only 45 % of the expected one. It is on this variant of partial compensation that the result of solving the problem of reactive power compensation in the power supply system was registered in [5].

The inclusion of the "Full compensation" option in the program with the introduction of the absence of source reactive power did not lead to a solution, and solving this problem by search engine optimization using a visual model [11–13] minimized the source reactive power with a capacitor close to C_k. (Meanwhile, the replacement of X_G by the limiting value X_G=0.794 Ohm gives a solution for the reactive power mode of full compensation, and in this variant on the load reaches 98.3 V, demonstrating the effectiveness of full compensation.)

The reasons for the impossibility of full compensation when using a shunt capacitor *C*, which shunt the load, are explained in Table 3, reflecting the study of the increase in reactive power *Qz* in the transmission line and *Q*Δ*C* of the additional capacitor ΔC (Fig. 8).

Table 3 illustrates the study of the increase in reactive power in the power line and additional capacitor.

$$\begin{pmatrix} iz \\ in \\ un \\ C \end{pmatrix} := \mathrm{Find}(iz, in, un, C) = \begin{pmatrix} 7.941-17.302i \\ 7.941-17.302i \\ 42.145-22.866i \\ 1\times 10^{-12} \end{pmatrix}$$

ANALYSIS OF THE RECEIVED MODE

$$ic := j\cdot w\cdot C\cdot un = 7.183\times 10^{-9} + 1.324i\times 10^{-8}$$

$$Ck = 7.582\times 10^{-4} \qquad C = 1\times 10^{-12}$$

$$|un| = 47.948 \qquad |iz| = 19.038 \qquad |in| = 19.038$$

$$Sn := 0.5\cdot un\cdot \overline{in} = 365.148+273.816i \qquad Sz := 0.5\cdot(e-un)\cdot \overline{iz} = 31.894+591.304i \qquad Sc := 0.5\cdot un\cdot \overline{ic} = -0i$$

$$Sn+Sz+Sc = 397.042+865.12i \qquad Se := \frac{e}{2}\cdot \overline{iz} = 397.042+865.12i$$

Fig. 10. Results of the initial mode system analysis for the case of high reactivity of a power line

$$\begin{pmatrix} iz \\ in \\ un \\ C \end{pmatrix} := \mathrm{Find}(iz, in, un, C) = \begin{pmatrix} 15.321-15.039i \\ 4.043-26.528i \\ 48.23-47.344i \\ 7.582\times 10^{-4} \end{pmatrix}$$

ANALYSIS OF THE RECEIVED MODE

$$ic := j\cdot w\cdot C\cdot un = 11.278 + 11.489i$$

$$Ck = 7.582\times 10^{-4} \qquad C = 7.5822\times 10^{-4}$$

$$|un| = 67.585 \qquad |iz| = 21.469 \qquad |in| = 26.834$$

$$Sn := 0.5\cdot un\cdot \overline{in} = 725.475+544.016i \qquad Sz := 0.5\cdot(e-un)\cdot \overline{iz} = 40.559+751.962i \qquad Sc := 0.5\cdot un\cdot \overline{ic} = -544.016i$$

$$Sn+Sz+Sc = 766.034+751.962i \qquad Se := \frac{e}{2}\cdot \overline{iz} = 766.034+751.962i$$

Fig. 11. Program corresponding to the mode of partial compensation

Table 3

Changes in reactive power transmission line and compensating shunt capacitance

C_k+ΔC	$\|i_z\|$	$\|u_n\|$	Q_z	$Q_{\Delta C}$
758.2	21.469	67.585	751.962	0
858.2	22.601	70.803	833.346	–78.744
958.2	23.993	74.096	939.205	–172.48
1,058.2	25.647	77.404	1,073	–282.334
1,158.2	27.547	80.639	1,238	–408.573
1,258.2	29.658	82.693	1,435	–550.128
1,358.2	31.926	86.433	1,663	–704.09
1,458.2	34.275	88.716	1,917	–856.41
1,558.2	36.618	90.402	2,188	–1,027
1,958.2	44.152	89.563	3,181	–1,512

The first column shows the values of the total capacitance $C_k+\Delta C$. The second and third columns show changes in current modules across the line $|i_z|$ and load voltage $|u_n|$. Exactly these values that determine the levels of reactive power in the power line and in the additional capacitor ΔC. Reactive powers Q_z and $Q_{\Delta C}$ (respectively, in columns 4 and 5) increase with ΔC. It should be noted that at the point of full compensation of reactive power regime, the algebraic sum of these powers should become zero. With an increase in ΔC the current consumption of this capacitor increases, which increases the current through the power line and, accordingly, increases the reactive power Q_z. However, this increases the voltage on the capacitor and its capacitance, which also leads to an increase in power $Q_{\Delta C}$. The question of achieving the full compensation condition is whether the $Q_{\Delta C}$ value will have time to "catch up" with the Q_z value before the voltage on the load starts to decrease due to an excessively high current in the transmission line. As can be seen from the Table 3, in the case under consideration, as the capacitance $C_k+\Delta C$ increases, the reactive power in the transmission line increases faster than the compensating reactive power of the additional capacity ΔC, the latter, when the value ΔC=2,000 μF reaches (the last line of Table 3) starts to decrease due to a reduction $|u_n|$. This is the physical picture of the impossibility of achieving the full compensation mode with the help of a shunt compensating capacitor C. The considered case of excessively large reactance of the transmission line may still be of practical interest in a systematic approach to the issue of full compensation of reactive power, which can significantly relieve primary sources of electrical energy.

Full compensation of reactive power in the considered variant of the parameters is achieved by introducing combined series-shunt compensation, carried out according to the scheme shown in Fig. 12.

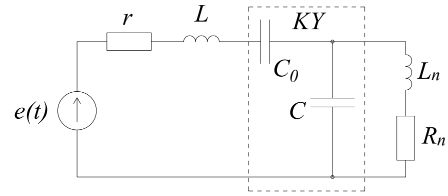

Fig. 12. System with combined series-shunt compensation

An additional capacitor C_0, is introduced here, providing the so-called series compensation [1, 4, 6]. Thus, the compensating device KU consists of the series capacitance C_0 and the shunt capacitance C (Fig. 12). Variations of series and shunt compensation capacitances can create conditions for the full compensation of reactive power in the power supply system in cases where the shunt compensation is capable of providing only partial compensation of reactive power. Fig. 13 shows a program for calculating the full compensation mode when using series and shunt capacitors.

SEARCH ENGINE OPTIMIZATION UNIT Given

$$iz = \frac{e - un}{z + \frac{1}{j\cdot w\cdot C0}} \quad un = zn\cdot in \quad in = iz - j\cdot w\cdot C\cdot un \quad Im\left(e\cdot \overline{iz}\right) = 0 \text{ FULL COMPENSATION}$$

$$Im(C) = 0 \quad Im(C0) = 0 \quad Re(C) > 0 \quad Re(C0) > 0$$

$$\begin{pmatrix} iz \\ in \\ un \\ C \\ C0 \end{pmatrix} := Find(iz, in, un, C, C0) = \begin{pmatrix} 30.3243 \\ 27.9975 - 25.313i \\ 94.6629 - 8.7014i \\ 8.5116\times 10^{-4} \\ 1.0696\times 10^{-3} \end{pmatrix}$$

ANALYSIS OF THE RECEIVED MODE

$$ic := j\cdot w\cdot C\cdot un = 3.142\times 10^{-10} + 3.142i\times 10^{-8}$$

$$Ck = 7.582\times 10^{-4} \quad C0 = 1.07\times 10^{-3} \quad |iz| = 30.324$$

$$C = 8.5116\times 10^{-4} \quad |un| = 95.062 \quad |in| = 37.744$$

$$Sn := 0.5\cdot un\cdot \overline{in} = 1435.293 + 1076.292i \qquad ic := j\cdot w\cdot C\cdot un = 2.327 + 25.313i$$

$$Sc := 0.5\cdot un\cdot \overline{ic} = -1208.224i \quad Snmax := 0.5\cdot e\cdot \overline{\left(\frac{e}{zn}\right)} = 1588.278 + 1191.012i$$

$$Sz := 0.5\cdot (e - un)\cdot \overline{iz} = 80.922 + 131.932i$$

$$Se := \frac{e}{2}\cdot \overline{iz} = 1516.214 \quad Sn + Sz + Sc = 1516.214$$

Fig. 13. Program for calculating the full compensation mode when using series and shunt capacitors

This program differs from the previous ones in introducing into consideration an additional optimization variable C_0, corresponding to the capacitance of a series capacitor with an initial value C_0=1. In the C_0 system model, it is easily taken into consideration in the first equation of the search optimization unit, where the complex resistance of the series capacitance is taken into consideration in the denominator of the right-hand side as an additive to the resistance z of the transmission line. The full compensation mode, as can be seen from the solution, is provided with compensator capacitances C=851.27 μF and C_0=1,069.7 μF. The voltage level at the load reaches 95.063, which corresponds to the load power supply system described in [5].

The summary Table 4 allows us to compare the operating parameters of the third test system for the initial mode, partial shunt compensation mode and full compensation mode.

Analysis of the data presented in Table 4 clearly shows all the advantages of the full reactive power compensation mode in comparison with any other mode.

Table 4

Modes for source mode, partial shunt compensation mode and full compensation mode

Parameter	Without compensation	Partial compensation	Full compensation
Cross capacitor condenser	0	758.2	851.27
Capacity of series capacitor	∞	∞	1,069.7
Power Line Current Amplitude	19.038	21.469	30.325
Load voltage amplitude	47.95	67.585	95.063
Total power consumed by the load	365+*j*274	725.5+*j*544	1,435+*j*1,076
Full power consumed by power line and series capacity	31.9+*j*591	40.6+*j*752	80.9+*j*132
Full power consumed by the shunt capacitor	0	–j544.02	–*j*1,208.4
Total power delivered by source	397+*j*865	766+*j*752	1,516.2

7. Discussing the results of reactive power compensation models analysis and optimization in the power supply system

The materials presented in the article show that the developed mathematical models using search engine optimization and implemented in the Mathcad system made it possible to solve all the assigned tasks of analyzing and optimizing the modes of reactive power compensation. First of all, it is shown that the traditional method of selecting compensator parameters, focused on compensation of reactive power only loads, saves residual reactive power in the system. This mode is not optimal from the point of view of the electricity source, since it continues to consume the reactive component of the total power. In the considered variants with a relatively small reactance of the power line, it is possible to provide full compensation due to a slight increase in the capacity of the shunt compensating device. The calculations showed that in the full compensation mode, the voltage and power at the load can significantly increase as compared with the partial compensation mode. The calculations carried out using optimization methods made it possible to show that the share of compensated reactive power due to the incremental increase in the capacity of the shunt compensator exactly corresponds to the reactive component of the power of the transmission line. The study of the system parameters variant, when the reactance of the power line is relatively large, showed that the possibilities of shunt compensation to ensure full compensation of reactive power are limited. Calculations on the mathematical model allowed us to give a physical interpretation of this phenomenon, which is associated with a decrease in the voltage on the compensating capacitor. This, in turn, reduces the reactive power compensation it uses. In this case, it is proposed to use a combined series-shunt compensation to achieve full compensation with the inclusion of two capacitors in the compensation device circuit. It is shown that the parameters of such a compensator, providing full compensation of reactive power, are also calculated using the mathematical models presented in the article based on search optimization.

The use of the proposed approaches ensures the achievement of high accuracy of the full compensation mode and minimizing the cost of computer time for research. The studies outlined in the article are a further development of the search optimization method proposed in the works by authors of [11–13] as applied to the tasks of improving the energy performance of electrical systems. It is intended to further develop the approaches proposed in the article as applied to power supply systems with non-linear loads and reactive power compensators on semiconductor elements.

12. Conclusions

1. Application of the constructed mathematical models of power supply systems allowed us to fully analyze and optimize the modes in a power supply system under various parameters for the system and the compensating device. This is predetermined by the inclusion to the program of the model, along with the component and topological equations, of conditions for finding a solution by optimization based on the assigned criteria for the full compensation.

2. Using the traditional approach to calculating the parameters of the reactive power compensator does not provide for the complete compensation of reactive power. Partial compensation of reactive power, depending on the parameters of the power line, leads to a mode with a power shortage in the load of about 20–40 %. Using the methods of forming mathematical models based on search optimization proposed in the article, it was possible to accurately calculate the parameters of a compensating device that provides full compensation of reactive power in the system. Owing to full compensation, a mode is set that is optimal for all energy indicators.

3. The conditions under which shunt compensation is unable to provide full compensation occur with an increase in the impedance of the transmission line, when an increase in capacitor capacitance causes a decrease in the voltage across it, and, consequently, a decrease in reactive power consumed by the capacitor. In this case, the optimal mode can be achieved by using a combined series-shunt compensation of reactive power, which allows you to bring the power factor to the maximum single value.

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