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
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 hydrogenator 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]

\[ 
\Delta Q_C = P(tg\phi_1 - tg\phi_2),
\]

where \( \Delta Q_C \) is the reactive power, compensated by a battery of capacitors; \( P \) is the active power consumed by the load in which compensation is performed; \( \phi_1, \phi_2 \) 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 \( U_s \) is determined from the following formula:

\[ 
C = \frac{\Delta Q}{3\omega U_s^2},
\]

where \( \omega \) 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 regards to one of the phases.

![Fig. 1. Generalized power supply system with a reactive power compensator](image)

In this system $e(t)$ is the sinusoidal power supply; $z_n$ is the load impedance of active-inductive nature: $zn=R_n+jx_n$. 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: $z_n=0.7+j0.005; z=0.1+j0.001; e(t)=100$. 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](image)
capacitive power. Summation of the passive elements $S_p + S_t + S_c$ and comparison of this sum with the power $S_c$ 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 $U_{\text{reduced}}$, and, consequently, the shortage in load power is $S_p = -834.7 + j1,873$. 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 ($Re(S_p) = 119.245$ W). It should also be noted that the source is loaded with a significant reactive power ($Im(S_p) = 22.47$ VAr).

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

It is clear from the solution that $C-C_4$ 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 ($S_p = -1,123.7 + j2,521$). It has been achieved through to a decrease in the current through the power line ($i_n = 23.00$), and the losses decreased ($Re(S_p) = 26.59$). At the same time, the reactive power in the system is not fully compensated, since the source of electricity gives off reactive power $Im(S_p) = 83.5$ VAr.

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

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

Fig. 2 shows the unlocked option $C=10^{-12}$, which a priori provides for a very small value of capacitance $C$ of the capacitive power. Summation of the passive elements $S_p + S_t + S_c$ and comparison of this sum with the power $S_c$ of the active element makes it possible to check the power balance [1–3].

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

Here, the operator $I_n = (e^{-j\varphi}i)$ is unlocked, 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 ($|U_{\text{in}}| = 97.431$ V). The capacitance of the compensating capacitor increased to $C = 1,747$ μF, which is slightly higher than the capacitance value $C_4 = 1,691$ 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 $|i_n| = 23.248$. 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

| Parameter | Without compensation | Partial compensation | Full compensation |
|-----------|----------------------|----------------------|-------------------|
| Capacity of the compensating condenser | $10^{-12}$ | $1.691 \times 10^{-3}$ | $1.747 \times 10^{-3}$ |
| Load current amplitude, $i_w$ | 48.835 | 56.656 | 56.956 |
| Power Line Current Amplitude, $i_z$ | 48.835 | 23.061 | 23.248 |
| Load voltage amplitude, $u_w$ | 83.983 | 97.431 | 97.948 |
| Total power consumed by the load, $S_n$ | $835+1.1873$ | $1.123+1.2521$ | $1.135+1.2547$ |
| Full power consumed by power line, $S_z$ | $19.25+374.6$ | $26.59+83.4$ | $27.02+84.9$ |
| The total power consumed by the capacitor, $S_C$ | $-j0$ | $-j2.521$ | $-j2.632$ |
| Total power delivered by source, $S_e$ | $953.9+2.2472$ | $1.150+83.54$ | $1.162.4+j0$ |

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:

$$z = z_e = 0.7 + jw0.005.$$  

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.
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, \( C_k \) | 0 \( \mu \text{F} \) | 1691 \( \mu \text{F} \) | 2026.4 \( \mu \text{F} \) |
| Load current amplitude, \( i_a \)                | 29.075               | 47.525               | 53.114            |
| Power line current amplitude, \( i_L \)           | 29.075               | 19.345               | 23.669            |
| Load voltage amplitude, \( u_a \)                | 50.0                 | 81.7                 | 91.341            |
| Total power consumed by the load, \( S_L \)       | 296+j664            | 791+j1,774           | 987+j2,216        |
| Full power consumed by the power line, \( S_p \)   | 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 \( \Delta C \), 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 \( \Delta C \), which compensates for the reactivity of the transmission line. It is impossible to directly calculate the additional capacitance \( \Delta C \) 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 \( \Delta C \) (Fig. 8) are found, the value \( \Delta C = jDC \), which provides the same reactive power consumption by the capacitor \( \Delta C \), which consumes inductive resistance \( \text{Re}(Z) \) 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 \( \Delta C \).

Share control PM in \( z \):

\[
\text{iDC} = 1 + j, \quad \text{DC} = 10^{-6}
\]

Given

\[
\text{Im}(\text{Se}) = -\text{Im}(0.5\times\text{un} \text{DC})
\]

\[
\text{Im}(\text{DC}) = 0
\]

\[
\left(\frac{\text{DC}}{\text{iDC}}\right) = \text{Find}(\text{DC}, \text{iDC}) = \left(\begin{array}{c}
5.63374 \\
0.12927
\end{array}\right)
\]

\[
C - C_k = 5.63374 	imes 10^{-5}
\]

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 \( \Delta C \) 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 \( \Delta C \), 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 \( S_{SG} = 15 \text{ MVA} \) and a voltage of \( U_p = 6,300 \text{ V} \). The internal resistance of the generator is taken to be \( Z_G = 0.066 + j3.2 \). When the resistance of the power line is \( Z_e = 0.11 + j0.063 \). The load resistance is assumed to be \( Z_L = 2.015 + j1.511 \). 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

\[
2 \frac{0.63^2}{15} = 2.646. \tag{5}
\]

Relative value of a synchronous generator inductive resistance is

\[
x' = \frac{X_n}{x_n} = \frac{3.2}{2.646} = 1.209. \tag{6}
\]

which is much more in comparison with the range \( X' = 0.08 \pm 0.3 \) for synchronous turbo and hydrogenerators [10]. Even the upper limit estimate \( X' = 0.3 \) leads to the maximum permissible generator resistance

\[
X_G = 0.3 \cdot 3.646 = 0.794 \text{ Ohm.} \tag{7}
\]

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 \textit{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 \( C_k = 758.2 \mu F \), 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 \( X_G = 0.794 \text{ Ohm} \) 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 shunts the load, are explained in Table 3, reflecting the study of the increase in reactive power \( Q_z \) in the transmission line and \( \Delta Q \) of the additional capacitor \( \Delta C \) (Fig. 8).

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

\[
\begin{align*}
\text{ANALYSIS OF THE RECEIVED MODE} \\
\text{ic} & := j \cdot w \cdot C \cdot \text{un} = 7.183 \times 10^{-9} + 1.324i \times 10^{-8} \\
Ck &= 7.582 \times 10^{-4} \quad C = 1 \times 10^{-12} \\
\end{align*}
\]

\[
\begin{align*}
\text{Sn} & := 0.5 \cdot \text{un} \cdot \text{in} = 365.148 + 273.816i \\
\text{Sz} & := 0.5 \cdot (e - \text{un}) \cdot \text{i} = 31.894 + 591.304i \\
\text{Sc} & := 0.5 \cdot \text{un} \cdot \text{ic} = -0i \\
\text{Sn} + \text{Sz} + \text{Sc} & = 397.042 + 865.12i \\
\text{Se} & := \frac{e}{2} \cdot \text{i} = 397.042 + 865.12i \\
\end{align*}
\]

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

\[
\begin{align*}
\text{ANALYSIS OF THE RECEIVED MODE} \\
ic & := j \cdot w \cdot C \cdot \text{un} = 11.278 + 11.489i \\
Ck &= 7.582 \times 10^{-4} \quad C = 7.582 \times 10^{-4} \tag{12}
\end{align*}
\]

\[
\begin{align*}
\text{Sn} & := 0.5 \cdot \text{un} \cdot \text{in} = 725.475 + 544.016i \\
\text{Sz} & := 0.5 \cdot (e - \text{un}) \cdot \text{i} = 40.559 + 751.962i \\
\text{Sc} & := 0.5 \cdot \text{un} \cdot \text{ic} = -544.016i \\
\text{Sn} + \text{Sz} + \text{Sc} & = 766.034 + 751.962i \\
\text{Se} & := \frac{e}{2} \cdot \text{i} = 766.034 + 751.962i \\
\end{align*}
\]

Fig. 11. Program corresponding to the mode of partial compensation
The first column shows the values of the total capacitance $C_0 + \Delta C$. 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 $\Delta C$. Reactive powers $Q$ and $Q_{AC}$ (respectively, in columns 4 and 5) increase with $\Delta C$. 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 $\Delta C$ the current consumption of this capacitor increases, which increases the current through the power line and, accordingly, increases the reactive power $Q$. However, this increases the voltage on the capacitor and its capacitance, which also leads to an increase in power $Q_{AC}$. The question of achieving the full compensation condition is whether the $Q_{AC}$ value will have time to "catch up" with the $Q$ 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 $C_0 + \Delta C$ increases, the reactive power in the transmission line increases faster than the compensating reactive power of the additional capacity $\Delta C$, the latter, when the value $\Delta C=2,000 \mu F$ 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.

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.

Fig. 12. System with combined series-shunt compensation

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 $C \approx 851.27 \mu F$ and $C_0 \approx 1,069.7 \mu F$. 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.
The advantages of the full reactive power compensation mode in comparison with any other mode.

### Table 4

| Parameter                        | Without compensation | Partial compensation | Full compensation |
|----------------------------------|----------------------|----------------------|-------------------|
| Cross capacitor condenser        | 0                    | 758.2                | 851.27            |
| Capacity of series capacitor     | ∞                    | ∞                    | 1.0697            |
| 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 | 365.0+274            | 725.5+544            | 1.435+1.076       |
| Full power consumed by line and series capacity | 31.9+594          | 40.6+752            | 80.9+132          |
| Full power consumed by the shunt capacitor | 0              | −j544.02            | −j1.208.4        |
| Total power delivered by source  | 397.7+865            | 766.7+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.

### References

1. Hofmann W., Schlabbach J., Just W. Reactive Power Compensation: A Practical Guide. John Wiley & Sons, 2012. 274 p. doi: https://doi.org/10.1002/9781119967286
2. Arrillaga J., Watson N. R., Chen S. Power system quality assessment. John Wiley, 2000. 300 p.
3. Acha E., Agelidis V. G., Miller T. J. E. Electronic Control in Electrical Systems. Newnes, 2002. 464 p. doi: https://doi.org/10.1016/b978-0-7506-5126-4.x5000-7
4. Kudrin B. I. Elektrosnabzhenie promyshlennyh predpriyatiy. Lviv: Inzhiniring, 2006. 622 p.
5. Milykh V. I., Pavlenko T. P. Elektropostachannia promyslovych pidpriyemstv. Kharkiv, 2016. 272 p.
6. Gerasimenko A. A., Fedin V. T. Peredacha i raspredelenie elektricheskoj energii. Rostov-na-Donu: Feniks, 2006. 720 p.
7. Nanda P., Kumar Panigrahi C., Dasgupta A. Reactive power monitoring and compensation in a distribution network of modern power system // International Journal of Applied Engineering Research. 2017. Vol. 12, Issue 22. P. 12395–12402.
8. Gayatri M. T. L., Parimi A. M., Pavan Kumar A. V. A review of reactive power compensation techniques in microgrids // Renewable and Sustainable Energy Reviews. 2018. Vol. 81. P. 1030–1036. doi: https://doi.org/10.1016/j.rser.2017.08.006
9. Optimization of reactive power compensation for distribution power system with small hydro power / Han Y., Chen L., Ma H., Wang Z. // 2014 International Conference on Power System Technology. 2014. doi: https://doi.org/10.1109/power-con.2014.6993939
10. Kopylov I. P. Elektricheskie mashiny. Moscow: Vysshaya shkola, 2004. 607 p.
11. Yagup V. G., Yagup E. V. Primenenie optimizatsionnyh metodov dlya resheniya zadach uluchsheniya pokazateley elektricheskikh sistem. Kharkiv: HNUGH im. A. N. Beketova, 2017. 170 p.
12. Yagup V. G., Yagup K. V. Synthesis of electric system in time domain by searching optimization method // Tekhnichna elektrodynamika. 2015. Issue 2. P. 24–29.
13. Yagup V. G., Yagup K. V. Determination of reactive power compensation mode in four-wire three-phase electric power supply system using search engine optimization // Tekhnichna elektrodynamika. 2016. Issue 1. P. 60–66.