DEVELOPMENT OF METHODOLOGY FOR CALCULATION OF OPTIMAL DISTRIBUTION OF ELECTRIC POWER BETWEEN POWER UNITS OF CONDENSING POWER PLANT

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Optimization methods are used to solve many problems in the field of energy. One of such tasks is the problem of optimal redistribution of power between power units in order to achieve minimum fuel consumption. This is especially important for powerful condensation power plants, where even relatively small fuel savings have significant economic effect.

The article is devoted to description of developed method of such optimization, based on the application of differential evolution, which has many advantages over the "classical" methods of optimization. In particular, it was the global rather than the local extremum of the objective function that could be found; it was also easy and powerful to use with modern software.

Differential evolution method is organized in the library SciPy of Python programming language, so calculation program was developed in this language to solve the problem. The work considers algorithm and structure of the developed program, as well as the procedure for preparing initial data and calculation process using example of a specific condensing power plant. Modules used in the program to populate the data arrays are mentioned, as well as to output the results in the form of high-quality graphs.

With the help of the program, diagram of the optimal redistribution of capacities between power units for any total capacity of the power station is constructed. Also, for entire power range of the power plant, nominal fuel consumption and fuel economy are calculated when implementing the optimal redistribution of capacity in comparison with an even distribution.

Obtained software product, available to everyone on the website of the authors, allows not only to study the practical application of differential evolution method, but also to create programs based on it to solve other optimization problems, some of which are mentioned in the article.

Keywords: *optimization, power redistribution, evolutionary methods, turbine power, differential evolution method, Python language.*

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Introduction

Modern condensing power plants (CPPs) typically have several power units, each with its own experimentally determined actual fuel consumption dependence on generated power (discharge characteristic).

This work is aimed at developing a methodology for determining the redistribution of the total generating capacity of a power plant among individual power units to obtain the lowest total fuel consumption.

Research methods and tools

The problem under consideration relates to optimization. Such problems can only be solved by utilizing precise mathematical techniques. Usually, a solution exists but can only be found using numerical methods, which are currently implemented using a computer.

The simplex method [1], the gradient method, Newton's method [2], etc., are among the numerical methods that have been previously used. However, these methods are only applicable

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for a specific type of optimization problem and have significant limitations in terms of the form and complexity of the equations, as well as the number of conditions imposed.

To avoid these limitations, heuristic methods have been used in recent years, in which the search for a solution follows a different pathway each time the program is run, but ultimately leads to the same result. These methods are usually based on analogies from living nature, such as studying the development of bee colonies or ant colonies, or, more generally, on the synthetic theory of evolution [3].

The differential evolution method [4], which is based on generating initial random values of factors and applying evolutionary principles, such as cross-breeding, mutation, and artificial selection of specimens with the best characteristics to them, is one of the most relevant and universal methods for finding an optimal solution. Constructing a population of factors refers to each stage of obtaining intermediate values (iteration). The differential evolution method is based on the simultaneous employment of regular and random processes, and as a result, it allows for the global rather than local extremum of the optimized function to be found.

When improving load redistribution between power units, it seems fair to employ the differential evolution method since it works reliably even with complex discharge characteristics. It is necessary to assess the degree of perfection of the method, and other advantages and disadvantages, as well as to develop recommendations for its further application to other optimization problems in the energy industry.

Results and discussion

The initial data for optimization are the discharge characteristics of the power units of the power plant, including the dependence of the specific (per unit of power) or physical consumption of fuel on the generated electric power.

Table 1 presents such dependences for a power plant with four power units based on condensing steam turbines K-100-90 for driving electric generators with the initial steam parameters (pressure 8.8 MPa; temperature 530 ºC, and final pressure 4 kPa), as an example. The maximum power at the electric generator terminals was 110 MW, and the minimum permissible power was 30 MW [5].

Table 1 was compiled using operational power unit data, and the specific consumption of equivalent fuel b_i, kg/(kW • h), was measured for each generated power N, MW, where i is the power unit number. The physical consumption of the equivalent fuel B_i, kg/s was calculated and added to the table using these data and *Microsoft Excel* spreadsheets.

$$B_i = \frac{N \cdot b_i}{3.6}.$$

Subsequently, consumption characteristics graphs were plotted in *Microsoft Excel* for all power units, as presented in Figure 1.

Using these characteristics, the optimization problem must be addressed, in which such powers of each power unit N_i should be determined for a known capacity of the power plant N, so that power plant B consumes

Table 1.

Consumption characteristics of power units of the investigated power plant

N, MW	b_1, kg/(kW • h)	b_2, kg/(kW • h)	b_3, kg/(kW • h)	b_4, kg/(kW • h)	B_1, kg/s	B_2, kg/s	B_3, kg/s	B_4, kg/s
30	0,488	0,471	0,527	0,443	4,07	3,93	4,39	3,69
40	0,434	0,427	0,445	0,408	4,82	4,74	4,94	4,53
60	0,369	0,358	0,336	0,344	6,15	5,97	5,60	5,73
80	0,338	0,341	0,321	0,329	7,51	7,58	7,13	7,31
100	0,32	0,333	0,325	0,312	8,89	9,25	9,03	8,67
110	0,313	0,331	0,339	0,302	9,56	10,11	10,36	9,23

the least amount of fuel (equal to the sum of fuel consumption for power units B_i).

These conditions can be presented as follows:

$$N = N_1 + N_2 + N_3 + N_4, \qquad (1)$$

$$B = B_1 + B_2 + B_3 + B_4 \to \min. \qquad (2)$$

In the considered optimization problem, the condition under Eq. (1) is a constraint, and the condition under Eq. (2) is an objective function. To solve the problem for each power unit, the mathematical fuel consumption dependence on power $B_i = f(N_i)$ should be determined. This can be done by determining the best approximation dependences for the graphs in Figure 1.

In *Microsoft Excel*, the approximation was performed by plotting trend lines for each graph. The polynomial approximation by third-order curves was the most suitable, providing the best approximation curves to the initial graph. The following dependencies were obtained for the discharge characteristics of the power units considered:

$$\begin{cases} B_1 = 1 \cdot 10^{-6} N_1^3 - 0.0002 N_1^2 + 0.0826 N_1 + 1.768 \\ B_2 = 1 \cdot 10^{-6} N_2^3 - 4 \cdot 10^{-5} N_2^2 + 0.0667 N_2 + 1.9838 \\ B_3 = 5 \cdot 10^{-6} N_3^3 - 0.0003 N_3^2 + 0.0431 N_3 + 3.337 \\ B_4 = -2 \cdot 10^{-6} N_4^3 + 0.0005 N_4^2 + 0.0423 N_4 + 2.1224 \end{cases}$$

$$(3)$$

To solve the aforementioned problem, it is convenient to use the *Python* programming language, for which there is a special library of mathematical methods called *SciPy* [6], which includes a differential evolution method implementation [7].

The *Python* language is easy to learn, and the differential evolution method used in this work, which is presented in the form of a special command, is also easy to use and does not require special knowledge of its characteristics. The command parameters can also be fine-tuned, and one of 12 strategies for solving and parallelizing resource-intensive tasks on several processors can be selected. The default settings of the method are suitable for achieving the aim of this work.

The algorithm of the developed *Python* program consists of the following parts:
1. Import of the required commands *NonlinearConstraint* (nonlinear limitation), Bounds (boundaries of the solution search), and *Differential_evolution* from the *Scipy*. optimize optimization library. The *Numpy* module [8] was also imported to perform operations with data arrays, as well as the *Matplotlib.pylab* [9] module for displaying intermediate and final results of calculations as graphs.
2. Assigning the value $N = 200$ MW to a variable representing the total capacity of a power plant as an example.
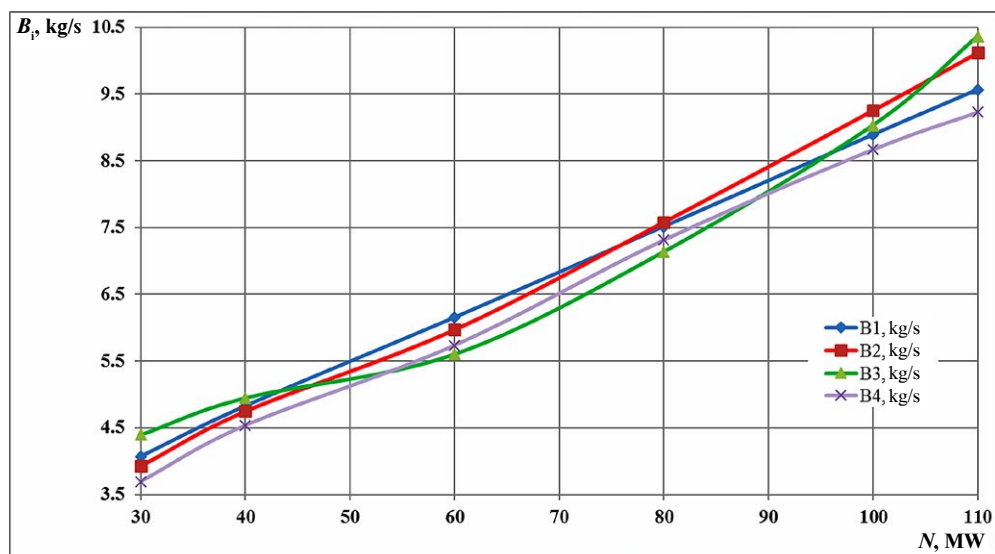

Fig. 1. Consumption characteristics of the investigated power units

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3. Input of the condition under Eq. (1) using the lambda function [10] and the *NonlinearConstraint* command.

4. Creation of the objective function under Eq. (2), which will be used as one of the parameters of the *Differential_evolution* command, along with the condition under Eq. (1). The values of the power N_i and the equivalent fuel consumption B, obtained at each iteration (ap proximation of the calculation process), were stored in arrays.

5. Using the *Bounds* command, define the smallest and largest allowable values for N_i variables, which are equal to 30 MW and 110 MW, respectively, according to the task.

6. Application of the differential evolution method (*Differential_evolution*) and displaying the optimization results for a given station power N on the screen.

7. Using the *Matplotlib* command module to display the calculated changes in the factors N_i as a function of the iteration number, as presented in Figure 2. The graph colors for each power unit correspond to those in Figure 1.

The evolution of changes in the factors N_1–N_4 upon searching for their optimal values corresponding to the minimum value of the objective function B is presented according to these graphical dependencies. At each start of the program, the two pathways (Figure 2) were different, as will the number of iterations required to provide a solution.
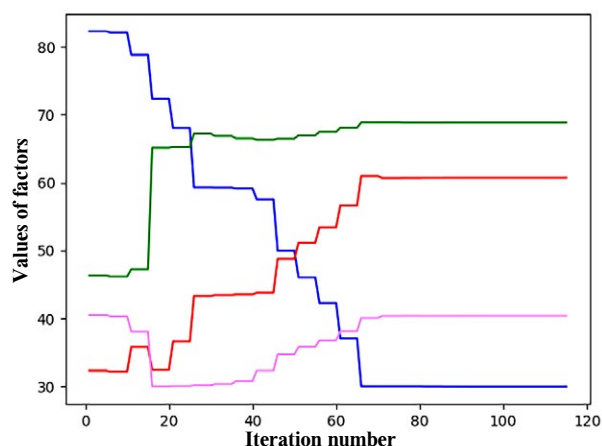
Despite the different evolutionary pathways of the optimized system from the initial random values, the found optimal values of the factors are equivalent at each start. Since a high degree of result accuracy was selected, the values remained unchanged at the last iterations.

For the total power N = 200 MW, the optimal capacity of the power units and the consumption of equivalent fuel (accurate to the second decimal place) were calculated (N_1 = 30.00 MW, N_2 = 60.73 MW, N_3 = 68.86 MW, N_4 = 40.41 MW; B = 21.23 kg/s).

Figure 3 presents the evolution of the total fuel consumption B toward the minimum value, with changes in the factors N_1–N_4, as shown in Figure 2.

To obtain the optimal redistribution of power unit capacities in the entire range of the possible total capacity of the power plant (N = 120−440 MW), the calculation program comprises a cycle for calculating the above parameters depending on N. The results are also displayed graphically.

Figure 4 presents the main dependence of the power unit capacities (factors N_1–N_4) on the power of station N, which is the study aim.

Figure 4 shows how to determine the power redistribution of individual power units N_1–N_4 at which the total fuel consumption at station B, reaches a minimum value for any station power N. The resulting diagram should be used to develop a control program for CPP power units.

Fig. 2. Changes in factors (capacities of power units N_1–N_4) depending on the iteration number
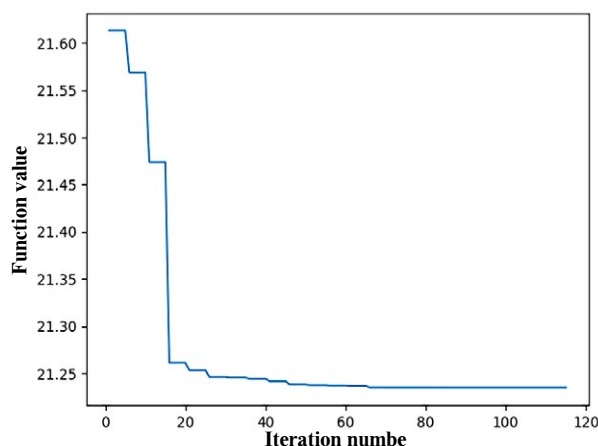

Fig. 3. Change in the value of the objective function (fuel consumption at power plant B) depending on the iteration number
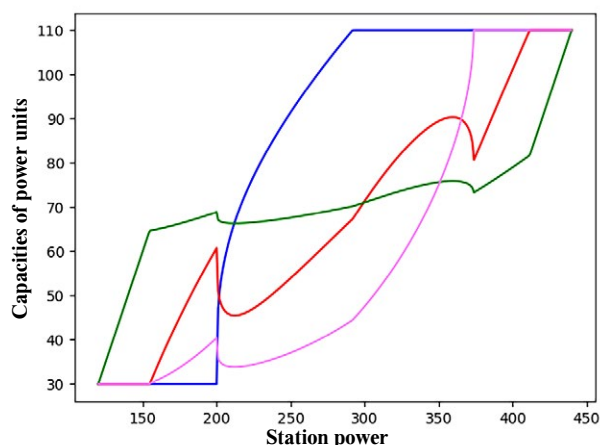
*Fig. 4. Redistribution of the capacities
of power units N_1–N_4 depending on the capacity
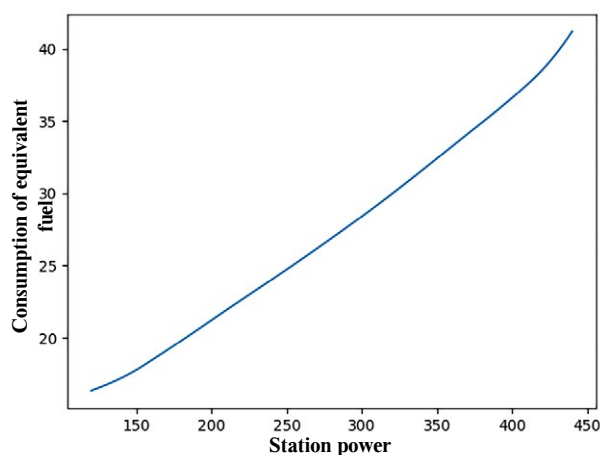of the station N*

*Fig. 5. Consumption of equivalent fuel
at power plants with optimal power distribution
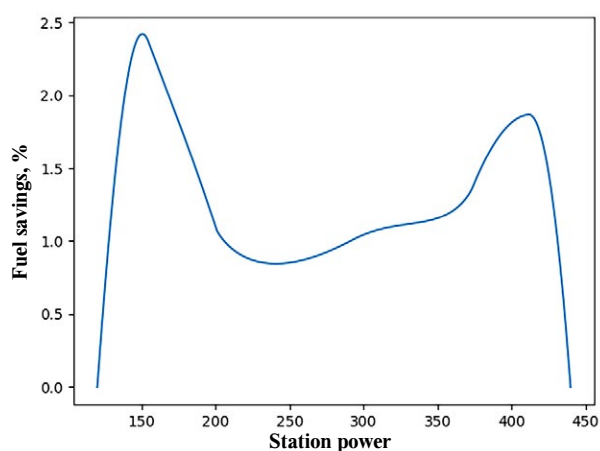between power units*

*Fig. 6. Fuel savings with optimal power
redistribution between power units versus
an even power distribution*

In Figure 5, the actual consumption of the equivalent fuel $B = f(N)$, is graphically represented for all possible plant capacities.

In the following research stage, the relationship between relative fuel savings and optimal redistribution of power unit capacities in comparison to the case of their uniform loading was assessed. With uniform loading, each power unit had a capacity $N_{unif} = N/4$, and fuel consumption B_{unif} is determined by Eq. (3), where all N_i are equal to N_{unif}. The relative fuel saving was determined by the following equation:

$$\delta = \frac{B_{равн} - B}{B_{равн}}100\%. \qquad (4)$$

Figure 6 shows the results of calculations using Eq. (4) for all possible power plant capacities.

Thus, a decrease in the relative fuel consumption at power plants when using the obtained diagram of the optimal power distribution between power units (Fig. 4) compared with their uniform loading can reach 2.4%, resulting in a significant increase in the economic efficiency of the considered powerful condensing power plant with steam turbines.

Conclusion
To achieve the aim of this work, the following tasks were solved:
- a brief comparison of the capabilities of widespread optimization methods and modern evolutionary methods, in particular, the differential evolution method used in this work;
- software tools for the implementation of the task of optimizing power redistribution between the power units of the power plant to ensure the minimum fuel consumption were selected and described;
- a methodology for the implementation of the specified optimization and visual display of the results using the *Python* programming language was fully developed;
- an example was calculated, demonstrating the relative simplicity and efficiency of applying the differential evolution method to solve the problem;
- a diagram of the optimal power redistribution between the power units

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of the condensing power plant was drawn up.

The code for the *Python* program developed during the research and discussed in this article is available for free study, application, and modification on the authors' website [11].

The method considered can be used to optimize power redistribution between the power units of any power plant (not only steam turbine CPPs but also thermal power plants, including gas turbine and steam gas turbines), as well as to solve other problems in the energy industry, such as:

- redistribution of liquid and gaseous fuel flows delivered from the point of production to the consumer [12];
- redistribution of electrical energy or energy carriers (steam or hot water flows) in the networks;
- optimization of investments in various energy facilities to maximize income [13].

A wide range of optimization problems can be solved using the methods provided and based on the algorithm of the developed program. The studies performed by the authors prove that the *Python* language is useful for creating not only programs for optimizing the characteristics of power systems, but also for solving other problems [14]. The differential evolution method has many advantages when compared to other numerical methods and differs from them in universality.

In addition to the fact that the automation of calculations in solving the problem considered is necessary, its implementation should result in a significant increase in the efficiency of power plant operation. The program developed can be used by university students and power plant operators to study the basics of power plant operation, and as a visual illustration of how to use the most relevant functions of the *Python* language for performing calculations in the energy industry.

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РАЗРАБОТКА МЕТОДИКИ РАСЧЕТА ОПТИМАЛЬНОГО РАСПРЕДЕЛЕНИЯ ЭЛЕКТРИЧЕСКОЙ МОЩНОСТИ МЕЖДУ ЭНЕРГОБЛОКАМИ КЭС

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Методы оптимизации используются при решении многих задач в области энергетики. Одной из таких задач является проблема оптимального перераспределения мощности между энергоблоками электростанции с целью достижения минимального расхода топлива. Это особенно важно для мощных конденсационных электростанций (КЭС), в которых даже относительно малая экономия топлива приводит к значительному экономическому эффекту.

Статья посвящена описанию разработанной методики такой оптимизации, основанной на применении современного метода дифференциальной эволюции, обладающего многими преимуществами перед классическими методами оптимизации. В частности, с его помощью можно найти именно глобальный, а не локальный экстремум целевой функции; также этот метод отличается простотой и широкими возможностями при использовании современных программных средств.

Очень удобно метод дифференциальной эволюции организован в библиотеке SciPy свободно распространяемого языка программирования Python, поэтому на этом языке разрабатывалась расчетная программа для решения поставленной задачи. В работе рассмотрены алгоритм и структура разработанной программы, а также порядок подготовки исходных данных и процесс вычислений на примере конкретной конденсационной электростанции. Упоминаются модули, используемые в программе для заполнения массивов данных, а также для вывода результатов в виде качественных графиков.

С помощью программы построена диаграмма оптимального перераспределения мощностей между энергоблоками для любой суммарной мощности рассматриваемой электростанции. Также для всего диапазона мощностей электростанции вычислен расход условного топлива и экономия топлива при реализации оптимального перераспределения мощностей по сравнению с равномерным распределением.

Полученный программный продукт, доступный всем желающим на сайте авторов статьи, позволяет не только изучать практическое применение метода дифференциальной эволюции, но также создавать на его основе программы для решения прочих задач оптимизации, некоторые из которых упомянуты в статье.

Ключевые слова: *оптимизация, перераспределение мощности, эволюционные методы, мощность турбин, метод дифференциальной эволюции, язык Python.*