Methodological Bases of Optimal Load Distribution at a Thermal Power Plant with a Complex Composition of Equipment, Taking into Account Market Requirements

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Abstract. The features of a mathematical model for optimizing the distribution of heat and electricity at a large thermal power plant with a complex composition of equipment as part of traditional heating units and a heating CCGT are considered. The selection and justification of optimization criteria at different stages of preparation and entry of the station to the electricity and capacity market is given. The disadvantages of the previously proposed optimal distribution algorithms are analyzed in relation to thermal power plants with a complex composition of equipment and with a complex scheme for the supply of electricity and heat. A method and algorithm for solving the problem are proposed based on the equivalence of the CHP equipment and the decomposition of the problem taking into account the schemes of electricity and heat output. The description of mathematical optimization methods is given, taking into account the peculiarities of the CCGT operating modes at reduced loads. The requirements for information support when integrating the developed algorithm into the application software of the automated process control system based on the PTC are given.

1. Introduction

Efficiency is one of the most important areas of development of existing technological processes. This report will describe a technique that allows you to find the operating modes of heat and electric energy production equipment that ensure its maximum efficiency, taking into account technological limitations. The criterion of production efficiency will be the amount of marginal profit received from the sale of production capacities. Optimal control of the operating modes of power equipment is the solution of two interrelated tasks that are relevant for modern energy: the choice of the composition of generating equipment and the optimal distribution of a given thermal and electrical load between the generating equipment, taking into account its current state [1-4].

When constructing an optimization model, it is necessary to take into account the features of the optimization method. The task is relevant for the regime optimization of the main and auxiliary equipment of power plants in a wide range of loads. The paper describes the construction of an optimization model of a thermal power plant, on the basis of which the calculation of modes that ensure its maximum efficiency is performed.

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As an example of a complex technological process, a thermal power plant (TPP) is considered, which produces heat and electricity (CHP), using gas and fuel oil as the main and reserve fuel. The majority of Russian thermal power plants are characterized by a change in the connected thermal loads depending on the season and weather conditions. The CHP has contracts for the purchase of fuel and the sale of electricity and heat. Margin profit is defined as the difference between the amount of money received for the sale of electricity and heat, and transferred for the fuel used. The profit of the station is obtained from the sale of electricity on the MDA market (the market for the day ahead) and the supply of heat to heat consumers with a constant tariff. The price of MDA electricity is highly volatile, so there is a need for regular planning and optimization of equipment operation modes. When working on the MDA market, the composition of the included generating equipment is determined, since the solution of the problem of choosing the composition of the included generating equipment (CCIGE) is made in advance. The planning horizon of the CCIGE can vary from 2 to 5 days [5].

When planning operating modes in the short term (from several hours to several weeks), the following requirements are usually taken into account:

- Production and distribution of a given amount of electricity between generating units;
- Release of the specified volumes of electricity and capacity in accordance with the planned schedule for each group of generation supply points;
- Heat supply to external consumers in accordance with the planned schedule of heat supply;
- Ensuring the necessary level of environmental cleanliness.

When planning the operation modes of thermal power plants for a longer term, it is necessary to add to the already formulated requirements:

- Reduction of annual equipment operating costs;
- Accounting for the implementation of planned measures that ensures the required level of reliability of the elements of the operated equipment;
- Ensuring reliable operation of the power system by meeting system requirements and restrictions.

A thermal power plant can have several components of income:

- Income from the sale of electricity on the day-ahead market (MDA) and the balancing market (BM), from the sale of heat, as well as the sale of electricity under regulated contracts (RC);
- Revenue from the sale of power in the competitive power take-off market sector (CPM);
- Income for participation in the market of system services (services for ensuring system reliability).

The costs include:

- Variable costs: payment of the cost of used fuel, environmental fee;
- Fixed costs (staff salaries, expenses for maintenance of equipment and repair companies, etc.);
- Penalties for non-fulfillment of obligations assumed.

Margin profit is defined as the difference between income and expense. It is assumed that the station will compensate for variable costs by selling electricity on the MDA and BM markets, as well as under RC contracts. The station provides fixed costs by selling capacity in the CPM market sector.

The income and expenditure from the sale of electricity and heat is the main optimization parameter for maximizing the marginal profit of the power plant. Intra-station planning of the equipment operation mode is short-term (from several hours to several days).

In the case when the composition of the equipment has already been agreed with the system operator and the dispatching schedule has been set, the problem of optimal mode management (operational planning) is solved. In this case, the goal of optimization is to minimize the cost of the fuel used and environmental collection, provided that the regime is maintained in accordance with the dispatching schedule and with the fulfillment of the requirements for thermal sampling to external consumers.

In the case when the station is planning the mode for the day ahead, the composition of the equipment is set. The problem of maximizing the difference between income and expenses, taking into account
the cost of electricity on the market, is solved with restrictions related to ensuring the requirements for heat sampling to external consumers.

In the case when the station plans the mode for several days ahead, it is possible to vary the composition of the equipment. The problem of choosing the composition of the included generating equipment is solved.

The high volatility of prices in the electricity market creates the need for regular planning of equipment operation modes, as well as creates restrictions on the optimization execution time. The task is relevant for the regime optimization of the main and auxiliary equipment of power plants in a wide range of loads.

Participation in the market sector of the competitive power take-off of the station is reduced to submitting a price application for the cost of a unit of generated power. The application is formed and submitted once a year. Further, the TPP operates in accordance with the established tariff. The revenue part in this sector becomes fixed. The expenditure part will be the costs during the repair company period, which are most often regulated. Optimization in this part of the market sector consists in choosing the optimal time for carrying out repair work. This task belongs to the tasks of long-term planning. The terms of the repair companies are strictly coordinated with the system operator of the central dispatch control.

The system services market allows the power plant to participate in the processes of ensuring the reliability of the power system. Optimization of the operating modes of equipment participating in the system services market is caused by the uneven schedules of electrical loads within the framework of integrated energy systems or free flow zones. The change in the structure of power consumption led to an increase in the unevenness of electrical loads. The share of the load of industrial production is decreasing, while the share of consumption for municipal needs and agriculture is growing. At night, the load is reduced to a minimum value, and during the daytime, the maximum load is reached. One of the features of the graphs of electrical loads is an increase in the rate of change of loads. To ensure the power reserve of the power system, power units (boilers, turbines, generators) can be in various reserve states: operational, cold, hot. In general, the main conditions of power units are considered to be: work, reserve, planned preventive maintenance (PPM), forced (emergency) downtime. The states through which the unit passes from one state to another (start, stop, work) are called intermediate. In each state, the unit has its own nature of operation, which affects the efficiency and reliability.

2. Formation of an optimization model

When forming an optimization model, the station equipment is decomposed into groups of elements. Further, each group of elements is described as an element of the optimization model. Currently, various optimization methods are used for CHP modes, and the choice of mathematical apparatus depends on the types of turbine installations, ways to represent the energy characteristics of turbines and boilers, the structure of heat release from the station. These methods include: linear programming, dynamic programming, mixed-integer linear programming (MILP) and others.

Boilers, turbines, and a high-and low-pressure steam collector are used as the main elements of the optimization model of the technological process of a cross-linked thermal power plant. Auxiliary equipment is taken into account in the form of amendments to the characteristics of the main equipment and in the form of additional own needs. The optimization model is built for a time period divided into several intervals. The description of the elements of the optimization model should be formed for each time interval. The formation of a spatio-temporal optimization model is necessary to take into account dynamic constraints such as the speed of load recruitment and discharge. It is also necessary to take into account the integral restrictions on the volume of fuel used for the period under consideration.

The optimization model can be used to solve the following tasks:

- planning the operating modes of the equipment, taking into account the price of the MDA for the day ahead;
- selection of the composition of the included generating equipment (CCIGE).
The solution of the CCIGE problem is performed in 5 days, the error in the forecast of the electricity price is on average 6-10%. The forecast of the MDA price is one of the main indicators on the basis of which planning is carried out.

The stages of forming an optimization test model of a thermal power plant include: formation of the station topology; formation of communication equations between components; setting the energy characteristics (EC) of the station equipment; introduction of time series defining restrictions on the operating modes of the station equipment; formation of an objective function for solving the optimization problem.

3. Consideration of environmental and reliability factors
As a rule, all methods are based on a single-criteria approach, such as minimizing fuel consumption or fuel costs, and other factors are not considered or taken as restrictions. These factors include environmental requirements, economic and reliability characteristics of the equipment. At the same time, it is obvious that the indicators of efficiency and reliability of power equipment tend to deteriorate both over time and from the modes of their operation. So, it is known that a power unit that has come out of major repairs and the same unit that has worked for several years after major repairs, both in terms of efficiency and reliability, have different indicators. The problem lies in the lack of methodological provisions for taking into account these long-term factors. This leads to the fact that when choosing the composition of generating equipment several days in advance, without taking into account long-term indicators, there is a great risk of an emergency shutdown, or unjustified fuel costs.

Taking into account several different factors in the optimization problem leads to the fact that the objective function can be quite complex. In this case, the application of methods often used in practice for solving the optimization problem, for example, the dynamic programming method or the Lagrange multiplier method, is difficult. Therefore, in this model, it is planned to apply the method of mixed-integer linear programming (MILP), where the objective function is minimized, and the components are represented as a set of variables connected by equalities and inequalities, there is also a restriction on the range of acceptable values.

Solving the problem of optimizing the operating modes of the station equipment, we can make some assumptions: the values reflecting external and internal balance relationships (electricity and heat generation, for example) are considered at each moment of time; it is assumed that the fuel reserves at the station are sufficient for the uninterrupted operation of the entire station during the time under consideration, and the values reflecting external restrictions (environmental restrictions, restrictions on water consumption, indicators for the reliability of electricity and heat supply) are considered set.

An optimization function that takes into account technical, economic, environmental and reliability factors can be represented as:

\[ F(x) = \lambda_1 F_1(x_1) + \lambda_2 F_2(x_2) + \lambda_3 F_3(x_3), \quad \lambda_1 + \lambda_2 + \lambda_3 = 1 \]  

(1)

where \( F_1(x_1), F_2(x_2), F_3(x_3) \) - the criterion of optimality, respectively, according to technical and economic indicators (minimum fuel or heat costs, etc.); reliability (minimizes the cost of providing a given reliability of electricity and heat supply); environmental factor (does not exceed the permissible norms that may change under adverse meteorological conditions); \( \lambda_1, \lambda_2, \lambda_3 \) - weight coefficients of the corresponding criteria; \( x_1, x_2, x_3 \) - optimization parameters.

When operating in basic modes, if the conditions for permissible emissions are met, preference is given to the \( F_1(x_1) \) criterion, in conditions of lack of capacity and if there is equipment at the station that has spent the calculated resource - \( F_2(x_2) \), under unfavorable meteorological and other conditions that require maximum reduction of emissions with flue gases while observing the balance equations for power and electricity generation - \( F_3(x_3) \).

When operating a power plant at partial loads, when flue gas emissions are significantly lower than the calculated ones, as well as under favorable weather conditions, the value of the weighting coefficients \( \lambda_1, \lambda_2 \) should be chosen based on the actual technical condition of the equipment.

When creating a set of programs that provide solutions to such complex problems, a decomposition method can be used at a thermal power plant - splitting a complex optimization problem into several
interconnected subtasks that form a system of algorithms, which includes: distribution of heat and electric load at fixed network and circulation water costs; formation of distribution options for a given heat load taking into account the limitations of each source; calculation of reliability characteristics of electricity and heat supply as a limiting factor, and others.

To take into account the environmental factor for the given subtasks, the optimal distribution of the electrical and thermal load is formed in the form of an equivalent fuel consumption characteristic. Next, for each point of the characteristic, the emissions for each chimney are calculated, then the total emissions in the location area are calculated and compared with the maximum permissible concentration (MPC). If the total emissions are less than the maximum permissible concentration, then the previously obtained solution is taken as the optimal one and the operating mode of the equipment is formed [6].

When taking into account the reliability factor according to the optimal criteria of economy and ecology, a number of options are selected that differ little from each other in terms of the value of the criteria. Then, based on the selected reliability criterion (the probability of finding the power unit in working condition, the availability coefficient, etc.), the specified or predicted states obtained using the selected subtasks are analyzed. After that, the option with the best reliability indicators is selected and the operating mode of the equipment is formed according to it.

Taking into account the reliability factor when choosing the optimal composition of working equipment can be carried out in two directions:

- according to the criteria of economy and ecology, the results are adjusted by the requirements of ensuring a given reliability in the form of mandatory restrictions, in all considered variants;
- in the form of conditional restrictions, which are characterized by certain economic functions and are taken into account when forming an economic criterion for choosing the optimal composition.

If the environmental conditions or the specified reliability are not met, a package of measures (regime, organizational, etc.) is formed to reduce harmful emissions or increase the level of reliability from among those possible in the real conditions of the station.

4. **Taking into account the peculiarities of the CCGT operation**

The task of finding the optimal mode of plant equipment is particularly relevant for CHP plants with a complex composition of equipment, including CCGT, due to the fact that the resource characteristics and dynamics of their changes over time for traditional steam turbines and gas turbines differ significantly from each other, which requires taking these factors into account when solving multi-criteria problems of optimizing the modes of operation of CHP equipment, in particular, when choosing ways to reserve the power of units when passing load failures in energy consumption schedules. But when choosing a strategy for carrying out maintenance and repair, the change in the indicators of efficiency and reliability of the TPP equipment over time was taken into account. Another feature of the CCGT is the dependence of the maximum and minimum permissible loads of the CCGT, and therefore the adjustment range, on external climatic conditions, in particular, on the outdoor air temperature, which, in turn, requires taking into account the optimal distribution of current electrical and thermal loads between the CCGT and traditional thermal units [7].

5. **Requirements for information support**

Currently, various methods and software packages have been developed for in-station optimization of equipment operation modes. Unfortunately, they have not found wide application in operation. The reason for the difficulty of using them in operation is a significant proportion of manual input of initial data to select the optimal mode for each task change. This is due to the lack of interaction interfaces between software complexes and automation systems installed at power plants.

The purpose of the research is to improve the methodological, technical and information support of the automated control system on the basis of modern software and hardware complexes for the practical implementation in an automated mode of the task of operational control of the operating modes of the
power plant equipment. At the same time, the optimization criterion, in addition to achieving the minimum fuel consumption (or total fuel costs, maximum profit of the station, etc.) for the station as a whole, is the most efficient use of the remaining equipment resource. This can be achieved if, when choosing the composition of generating equipment, especially when solving problems of passing dips in energy consumption schedules, in addition to the criteria of efficiency and reliability, we also take into account the factor that characterizes the overall reduction in the resource of generating equipment, both in the short and long-term time intervals. At the same time, of course, there is a need to monitor the current state of the equipment, take into account the changes in the resource of each unit under different operating modes, but at the same time it is possible to achieve a comprehensive solution to both the problems of efficiency and reliability, and maximum resource saving.

6. Conclusion
The presented methodology allows calculating the optimal operating mode of the equipment, taking into account technological limitations, not only in accordance with the criterion of maximum margin profit, but also taking into account the factor of reliability and environmental friendliness. The peculiarity and difference of the proposed studies in this direction is also the fact that CHPs with a complex composition of equipment, including heating units and aggregates, and combined-cycle gas installations will be considered. In addition, it is necessary to take into account the peculiarities of the operation of thermal power plants in market conditions, when power plants enter the electricity and capacity market. It is necessary to consider optimization tasks for all three stages of the CHP operation on the market: choosing the composition of the working equipment, choosing the optimal load of the CHP on the market for the day ahead (MDA) and optimization on the balancing market (BM) with a set of additional electrical load.

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