A formation of an approach to solving the problem of selecting the composition of the included generating equipment

A V Andryushin, E K Arakelyan, A V Neklyudov, Y Y Yagupova and T O Drobyshev

National Research University "MPEI",
Russia, 111250 Moscow, Krasnokazarmennaya, 14

Abstract. The article deals with the method of formation of optimization models for calculation of modes of operation of thermal power plants, as well as the software package on which the optimization models are formed. The formed model allows to calculate the optimal combination of the whole set of combinations of compositions and modes of operation of the thermal power plant equipment.

1. Introduction
Efficiency is one of the most important directions of development of existing technological processes. The article will describe a technique that allows you to find the operating modes of production equipment, ensuring its maximum efficiency, taking into account technological limitations. The criterion of production efficiency will be the value of margin profit received from production facilities. As an example of a complex process is considered a thermal power plant (TPP). The thermal power plant produces heat and electricity, using as fuel the main and reserve fuel (gas and fuel oil). Most Russian thermal power plants are characterized by changes in the attached thermal loads depending on the season and weather conditions. TPP has contracts for the purchase of fuel and 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 listed for the fuel used. The profit of the station is obtained from the sale of electricity on the RSV market (the market for the day ahead). The price of electricity day-ahead market has a high volatility. Therefore, there is a need for regular planning of equipment operation modes. At work in the RSV market the structure of the included generating equipment is defined. The solution to the problem of selection of the included generating equipment is made in advance. The planning horizon may vary in selection of the included generating equipment then 2 to 5 days.

Two main approaches to the selection of the included equipment are used in different electricity markets:
1) Self-balancing:
• Generators independently determine the feasibility of including their equipment
• The reason for the work may be previously concluded bilateral agreements or high spot prices
• The generators notify the System operator in advance of their decision to turn on or off
• If the System operator assumes excess of consumption over the volume of the equipment declared for work, he holds a competition for inclusion of additional volumes
(Nord Pool, United Kingdom, Australia)
2) Centralized selection:
• Generators are served to the System operator bids for the work comprising pairs of "price-number" and the value of the start-up and other costs associated with the production of e/e.
• The system operator selects the amount of generation required to cover the demand.
• The principle of selection is to minimize the total cost of generators to produce the required amount of electricity (PJM, New England).
Both approaches lead to the formation of an equilibrium price and ensure efficient production.

When building an optimization model, it is necessary to take into account the features of the optimization method. The problem is relevant for mode 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 thermal power plants, on the basis of which the calculation of modes that ensure its maximum efficiency.

2. Description of a simplified model of the station
In the formation of optimization models, is the decomposition of plant equipment on groups of items. Each group of elements is then described as an element of the optimization model.

Boilers, turbines, high and low pressure steam collectors are used as the main elements of the process optimization model. Additional 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 constructed for a period of time divided into several intervals. The description of the elements of the optimization model should be formed for each time interval. The formation of a space-time optimization model is necessary to take into account dynamic constraints such as the speed of recruitment and load dump. It is also necessary to take into account the integral restrictions on the volume of fuel used for the period under review.

The optimization model can be used to solve problems:
• planning of operation modes of equipment with regard to day-ahead market prices on the day ahead;
• the solution to the problem of selection of the included generating equipment;

The solution of the problem WSVGA runs to 5 days, the error of the forecast of electricity price is an average of 6-10%. Price forecast RSV is one of the main indicators on the basis of which planning is performed.

3. Component description turbine
Consider the simplified thermal scheme of the turbine. The power supplied to the turbine is determined by the expression:

\[ Q_0 = D_0 h_0 - D_{fw} h_{fw} \]  

(3.1)

If we assume that there are no leaks from the cycle, except for the consumption of steam from the selections, we can assume that \( D_0 = D_{fw} \), than

\[ Q_0 = D_0 (h_0 - h_{fw}) \]  

(3.2)

For turbines, specify the parameter characterizing the heat rate to generate 1 MW at different heat selections:

\[ q_{tg} = \frac{Q_e}{N_t} 10^3 = \frac{q_0 - \sum Q_s}{N_t} 10^3 \]  

(3.3)

\[ D_0 (h_0 - h_{fw}) = q_{tg} N_t 10^{-3} + \sum Q_s \]  

(3.4)

This equation can be considered as the basic balance equation.

Since \( q_{tg} \) is defined for the nominal mode of operation of the equipment, it is necessary to consider a group of amendments related to the deviation of the operating conditions of the equipment from the nominal.

Amendments to the main indicators of turbine units are given to the deviation of the values of the following factors, which have the most significant impact:
• Fresh steam pressure and temperature
• Exhaust steam pressure of the turbine unit in the condenser
• Ratio of feed water flow through HPH and fresh steam flow
• Temperature of feed water from the group of HPH
Temperature of the water at the entrance to the heaters
Exhaust steam pressure for each pipeline of the power units’ own needs mechanisms.

The extraction turbine with adjustable steam extraction can operate in condensing and cogeneration modes.

When operating in condensing mode the vacation couple in adjustable sampling is not performed. The energy characteristic of the turbine in this case is expressed in the same form as that of the condensation turbine.

When operating in cogeneration mode under heating heat consumption for turbine $Q_0$ refers to the flow provide the intended heat load $\sum Q_{x_i}$, the minimum pass steam into low-pressure part related to these streams the selections on the regeneration and compensation of heat losses on the turbine $Q_{pot}$

For each of the possible modes of operation of the turbine unit, its energy characteristics should be used.

3.1. Consider a turbine of type T as an example:
The specific gross consumption is determined by the expression:

$$ q = q(P_T, Q_T, N) \quad (3.1.1) $$

To determine the specific flow rate it is necessary to know the pressure $P_T$ in T selection.

The pressure in $P_T$ selection is determined by the temperature of the direct network of water on the saturation line with the adjustment for the resistance of the pipeline $k_r$ and the amount of underheating $dT$.

The temperature of the mains water is determined by the thermal extraction $Q_T$, the volume of mains water $G_m$ passing through the heater:

$$ T_{mp} = \frac{Q_T}{G_m} \times 1000 + T_s \quad (3.1.2) $$

Selection pressure is determined:

$$ P_T = P_{sr}(Tpr + dT) \times (1 + k_r) \quad (3.1.3) $$

Heat consumption per turbine:

$$ Q_0 = Q_T + \frac{q \times N}{1000} \quad (3.1.4) $$

Coolant flow rate is determined by:

$$ D_0 = \frac{Q_0}{h_0-h_{fw}} \quad (3.1.5) $$

The consumption of steam in the condenser:

$$ D_k = f(Q_T, D_0) \quad (3.1.4) $$

The pressure in the condenser is defined as:

$$ P_k = f(W_c, D_k, t_c) \quad (3.1.3) $$

Based on the above dependencies, the calculation is performed according to the flow of steam from thermal selection $Q_T$, generation $N$, consumption of network water $G_m$. A special calculation module was developed to perform the calculation. The set of points forming the characteristic surface of the equipment operation mode is shown in figure 1.
4. Taking into account the possibility of using different operating modes of the equipment

In the preparation of the optimization model to solve the problem of selection of the included generating equipment, the mode of operation of the equipment may be unknown. For completeness of the description of options of possible modes, it is necessary to perform calculation of all modes and to form a design of the turbine taking into account their possible switching. For T-turbines, the following modes are distinguished:
• Condensation (K)
• Single-stage selection mode (I)
• Two-stage selection mode (II)

For each of the modes and enter an additional parameter "Use" and set the restrictions of the form:

\[ K_{Use} + I_{Use} + II_{Use} = T_{Use} \]  (4.1)

Where K.Use, I.Use, II.Use, T.Use - Boolean variables

The following shows the relationship of the turbine parameters with the parameters of its modes of use:

- \[ T.N = K.N + I.N + II.N \]  (4.2)
- \[ T.Q_t = I.Q_t + II.Q_t \]  (4.3)
- \[ T.Q_0 = K.Q_0 + I.Q_0 + II.Q_0 \]  (4.4)

5. Boiler component description

The energy characteristic of the boiler expresses the relationship between the supplied and usefully used amount of thermal energy. The amount of heat received in the boiler is spent on the production of thermal energy gross, as well as to compensate for heat losses in the installation.

The equation of heat balance of the boiler:

\[ Q_p = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6shl + Q_6ohl \]  (5.1)

where \( Q_r \) – the available amount of heat; \( Q_1 \) – the production of thermal energy gross; \( Q_2 \) – heat loss with the outgoing gases; \( Q_3, Q_4 \) – heat loss, respectively, from the chemical and mechanical incompleteness of fuel combustion; \( Q_5 \) – heat loss from the external cooling of the boiler; \( Q_6shl \) – loss of physical heat contained in the removed slag; \( Q_6ohl \) – loss of cooling vents, nozzles, panels and beams, shot cleaning, not included in the circulation circuit of the boiler.

The equation for the gross efficiency of the boiler:

- Direct balance
  \[ \eta_{ge} = Q_{ge} / Q_{pf} + Q_{in} \]  (5.2)

- Reverse balance
  \[ \eta_{ge}^{(rev)} = 100 - q_2 - q_3 - q_4 - q_5 - q_6shl - q_6ohl \]  (5.3)

Development of power characteristics of boilers takes place taking into account the composition and characteristics of the burned fuel.

The energy characteristics of the boiler, as well as the characteristics of the turbine unit, are supplemented by amendments to the deviation of the values of external factors from the fixed conditions. These include: the temperature of cold air; the temperature of the feed water; the proportion of flue gas recirculation and others.

To describe the dynamic parameters of the turbine unit are introduced:
• Limitation on the rate of change in the volume produced by steam
• Minimum operating time limit if the equipment is switched on
• Minimum stop time limits in case of equipment shutdown
• Imposing a penalty for changing the value of the equipment parameter
• Limit the number of times the equipment is switched on/off during the period under review.

6. Contract
The contract element formalizes the process of buying and selling in the market. The contract is a structure that relates the volume and price of the sold/purchased quantity. A commercial contract can be specified for a specific time interval or for a group of intervals. The attributes of the contract include: the start and end of the contract, volume, and price.

7. Collector
Element Collector formalizes the laws of conservation of energy and mass. The sum of inputs is equal to the sum of outputs plus losses.

8. Approach to the formation of the optimization model
In this paper, the optimization problem is reduced to the form of Mixed Integer Linear Programming (Mixed Integer Linear Programming):

The objective function is minimized:

\[ f = \min \sum_i c_i x_i \]  

With the following restrictions:

\[ A_{eq} \cdot \vec{x} = \vec{b} \]  
\[ A_{ineq} \cdot \vec{x} \leq \vec{b}_{ineq} \]  
\[ l_b \leq \vec{x} \leq u_b \]

Each component of the vector \( \vec{x} \) corresponds to one of the types: B - binary, I - integer, C – continuous.

The optimization model involves components, each of which must be presented in the form described above. The process of representing a function as a set of variables between which linear relationships are defined in the form of equality and inequality, as well as restrictions on the range of permissible values below will be called "parameterization".

The relationships between the components of the model are described by linear equations.

9. Performing optimization calculations
After the description of all the elements of the equipment, setting the links between them and technological limitations, the price of the used fuels and the price for the sale of electricity in the RSV market sector are transferred to the optimization model. Then the optimization calculation is performed. Gurobi Version 8.1 is used as a solution library for the MILP task.

10. Economic effect of using the model
The economic effect achieved from the use of the thermal power plant optimization system can be from 1.5 to 6 % of the cost of the fuel used. The economic effect is calculated as the difference between margin profits when working on the actual mode and when solving the problem of choosing the composition of the equipment. for rice. 5 shows a plot of the changes in contribution margin depending on the scenario calculation.

The calculation time depends on the complexity of the optimization model and the number of degrees of freedom allowed for each piece of equipment.

The number of element parameterization variables is determined by the number of points that define the surface. To speed up the process of optimization calculation, it becomes urgent to
minimize the number of points describing the surface, taking into account the required accuracy. Figure 2 on the left is the original surface, on the right – after the reduction of points. When reducing the points when the requirement that the surface approximation error does not exceed 2% leads to an acceleration of the calculation of more than 5 times.

11. Summary
The described method allows to solve the problem of selection of equipment composition and planning of its modes for stations with cross-links and several GTR. The depth of planning is determined by the type of task to be solved. Optimization is carried out taking into account the cost and integrated restrictions on the amount of fuel used for the calculated period, the characteristics and configuration of the equipment, the cost of electricity on the market (set for each hour), dynamic restrictions on the operation of the equipment.

12. References
[1] Arakelyan E K, Pikina G A 2008 Optimization and optimal control: practical guide (Publishing house MPEI),
[2] Ivanov N S Theoretical and practical prerequisites for the creation of software to optimize the distribution of loads on TPP
[3] Ivashchenko V A, Fomin I N, Shulga T E Mathematical model and algorithm of operational control of generating equipment of TPP
[4] Lekukhovsky G V, Pospelov A A Calculation and rationing of thermal efficiency of thermal power plant equipment
[5] Vinnikov A Features of selection of the included generating equipment in the Russian energy market
[6] SheilaSamsatlia Nouri J. Samsatlib General model of mixed integer linear programming for the design and operation of integrated urban energy systems
[7] Hart W E, Laird K D, Watson J-P, Woodruff L D Pyomo — optimization modeling in Python

Acknowledgments
The research is supported by the Russian Science Foundation, grant № 19-19-00601