The optimization problems of CHP operation

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Abstract. The problem of enhancing energy and economic efficiency of Combine Heat and Power plant (CHP) is urgent indeed. One of the main methods for solving it is optimization of CHP operation. To solve the optimization problems of CHP operation, Melentiev Energy Systems Institute, SB of RAS, has developed a software. The software makes it possible to make optimization calculations of CHP operation. The software is based on the techniques and software tools of mathematical modeling and optimization of heat and power installations. Detailed mathematical models of new equipment have been developed in the work. They describe sufficiently accurately the processes that occur in the installations. The developed models include steam turbine models (based on the checking calculation) which take account of all steam turbine compartments and regeneration system. They also enable one to make calculations with regenerative heaters disconnected. The software for mathematical modeling of equipment and optimization of CHP operation has been developed. It is based on the technique for optimization of CHP operating conditions in the form of software tools and integrates them in the common user interface. The optimization of CHP operation often generates the need to determine the minimum and maximum possible total useful electricity capacity of the plant at set heat loads of consumers, i.e. it is necessary to determine the interval on which the CHP capacity may vary. The software has been applied to optimize the operating conditions for the real CHP plant. The efficiency of operating condition optimization and the possibility for determination of CHP energy characteristics that are necessary for optimization of power system operation are shown.

1. Introduction.

Combine Heat and Power plant (CHP) is one of the main facilities in electric power systems. Normally, cogeneration plants have various mix of equipment and complex flowsheets including the elements in which various physico-chemical processes occur. Besides, the condition of CHP equipment changes considerably in the process of operation. Therefore, the problem of enhancing energy and economic efficiency of CHP is urgent indeed. One of the main methods for solving it is optimization of CHP operation. Quite many papers [1, 2, 3, etc.] have been devoted to solution of this problem. However, they employed simplified models of equipment and did not foresee any adjustment of these models to the actual condition of the equipment.
To solve the optimization problems of CHP operation, Melentiev Energy Systems Institute, SB of RAS, has developed a software. The software makes it possible to make optimization calculations of CHP operation. The software is based on the techniques and software tools of mathematical modeling and optimization of heat and power installations [4,5]. Detailed mathematical models of new equipment have been developed in the work. They describe sufficiently accurately the processes that occur in the installations. The developed models include steam turbine models (based on the checking calculation) which take account of all steam turbine compartments and regeneration system. They also enable one to make calculations with regenerative heaters disconnected.

2. The optimization problems of CHP operation. There can be several optimization problems related to CHP operation [6, 7]. The considered software can solve any of them.

Problem 1. Minimization of fuel consumed by CHP boilers (or its total cost when burning different fuels) at a set electric load of the plant and heat loads of external consumers.

\[
\min_{X} B^{CHP}(x, y, N^{CHP}, Q_1, ..., Q_k),
\]

subject to:

\[
H(x, y, N^{CHP}, Q_1, ..., Q_k) = 0,
\]

\[
G(x, y, N^{CHP}, Q_1, ..., Q_k) \geq 0,
\]

\[
x^{\min} \leq x \leq x^{\max},
\]

where \(B^{CHP}\) – the total fuel consumption at CHP; \(x \in E_r\) – the vector of individual parameters to be optimized (flow rates of steam going into turbine condensers and extraction steam, pressure before control diaphragms of turbines, steam pressure in peak delivery-water heaters, etc.); \(y \in E_m\) – the vector of dependent parameters to be optimized (flow rates of live steam going into turbines, flow rates of bleed steam, electric capacities of turbines, bleed steam pressure, etc.) \(N^{CHP}\) – useful electric capacity of CHP; \(Q_i\) – a set load of the \(i\)-th external heat consumer; \(k\) – the number of external heat consumers; \(H\) – an \(m\)-dimensional vector function of equality constraints, includes equations describing the process links among the elements of the flowsheet, energy and material balances of the CHP flowsheet elements, etc.; \(G\) – an \(l\)-dimensional vector function of inequality constraints (includes lower and upper bounds on such dependent parameters as flow rates of live steam going into turbines, electric capacities of turbines, etc.); \(x^{\min}, x^{\max}\) – vectors of minimum and maximum values of vector \(x\).

The optimization of CHP operation often generates the need to determine the minimum and maximum possible total useful electricity capacity of the plant at set heat loads of consumers, i.e. it is necessary to determine the interval on which the CHP capacity may vary. This is reduced to solution of the two following problems.

Problem II. Minimization of the total useful electric capacity of CHP at set heat loads of external consumers.

\[
\min_{X} N^{CHP},
\]

subject to (2)-(4).
Problem III. Maximization of the total useful electric capacity of CHP at set heat loads of external consumers.

\[
\max_{X} N^{CHP}
\]  

subject to (2)-(4).

After problems II and III are solved problem I is solved for the obtained CHP capacities to determine the minimum fuel consumption.

For effective control of CHP operation it is often necessary to know the maximum useful electric capacity that can be obtained at the minimum flow rates of steam going into turbine condensers. This requires that problems III and I be solved at the fixed minimum flow rates of steam going into turbine condensers.

Solution of a set of the problems presented allows one not only to optimize the individual operating conditions of CHP but also to construct dependencies (energy characteristics) that relate fuel consumption at a plant with its total electric capacity at fixed heat loads. For this purpose the solutions to problems II and III are used to determine the minimum \(N^{CHP}_{\text{min}}\) and maximum \(N^{CHP}_{\text{max}}\) electric capacities of CHP. Then problem I is solved for several values of plant capacities lying in the determined interval \([N^{CHP}_{\text{min}}, N^{CHP}_{\text{max}}]\). The obtained CP capacities and the fuel consumption corresponding to them are used to construct the dependences that relate fuel consumption with electric capacity. These characteristics are necessary to distribute electric loads among power plants in power systems.

3. The software. The structure of the software intended to optimize CHP operation is presented in Figure 1. The software makes it possible to set in a convenient form the initial data on loads of external consumers, condition of CHP equipment, etc.; present the calculation results in the hierarchically organized flowsheets and tables. The software allows one to carry out calculations for optimal distribution of loads among CHP units and identify the main energy equipment.

Figure 1. Structure of the software.
In order to analyze the calculated operating conditions of CHP, a specialized information system was developed within the software. It makes it possible to store the optimal operating conditions in the database, make a sampling of operating conditions by the main parameters (electric capacity of CHP, heat load, etc.), restore the operating conditions for calculation, construct diagrams of change in the parameters under set operating conditions, and compare optimal operating conditions with real ones (set by the plant personnel).

4. An example of cogeneration plant operation optimization. The described software for optimization of CHP operation was applied by the real CHP plant. The plant consists of complex different-type energy facilities: 8 power boiler units with the total capacity 4000 t/h and 5 cogeneration turbine units. Brown coal is the main fuel. A simplified flowsheet is given in Figure 2.

Figure 2. A simplified flowsheet of CHP

Figure 3 presents the screen of the main software window. Table 1 shows comparison of the actual and optimal operating conditions for three variants of thermal and electric loads of the plant.
Figure 3. Main window of the software.

Table 1. Comparison of actual and optimal operating conditions

| Parameters                                      | Units   | Operating condition 1 | Operating condition 2 | Operating condition 3 |
|------------------------------------------------|---------|-----------------------|-----------------------|-----------------------|
| Electric capacity of CHP                       | MW      | 570                   | 464                   | 334                   |
| Heat load of CHP                               | Gcal/h  | 757.0                 | 590.8                 | 508.8                 |
| Temperature of direct/return delivery water    | ºC      | 117/68                | 94/60                 | 80/50                 |
| Flow rate of direct delivery water             | t/h     | 11883                 | 12129                 | 12374                 |
| Flow rate of makeup water                      | t/h     | 2910                  | 3008                  | 3357                  |
| Electric capacity of turbines:                 |         |                       |                       |                       |
| IIT-60-130/13 № 1                              |         | 57.6                  | 49.6                  | 49.0                  | 44.3                  |
| IIT-60-130/13 № 2                              |         | 52.5                  | 44.6                  | 40.4                  | 54.2                  | 46.9                  |
| T-175/210-130 № 3                              | MW      | 145.6                 | 164.9                 | 108.4                 | 112.3                 | 0                     | 0                     |
| T-175/210-130 № 4                              |         | 150.5                 | 159.9                 | 105.7                 | 105.1                 | 151.1                 | 112.0                 |
| T-185/220-130 № 5                              |         | 163.8                 | 150.9                 | 105.1                 | 159.1                 | 79.7                  | 130.8                 |
| Fuel consumption by CHP boilers                | tce/h   | 212.39                | 209.59                | 146.19                | 144.29                | 131.12                | 129.62                |
| Fuel saving by CHP                             | tce/h   | 2.8                   | 1.9                   | 1.5                   |                       |                       |                       |
As is seen from the Table, optimization of operating conditions for CHP leads to fuel saving within 1.1-1.3 %. An example of the energy characteristic of CHP that is constructed by the software for the heat load 1140 Gcal/h and the temperature of direct/return delivery water 150/70 °C is given in Figure 4.

![Energy characteristic of CHP](image)

**Figure 4.** Energy characteristic of CHP.

Analysis of the obtained energy characteristic shows that in the range 400-480 MW the electric capacity of CHP increases due to increase in electricity production at the minimum volume of steam to turbine condensers and in the range 480-655 MW due to additional electric capacity.

5. **Conclusions**

1. The software for mathematical modeling of equipment and optimization of CHP operation has been developed. It is based on the technique for optimization of CHP operating conditions in the form of software tools and integrates them in the common user interface.

2. The software has been applied to optimize the operating conditions of the real CHP plant. The efficiency of operating condition optimization and the possibility for determination of CHP energy characteristics that are necessary for optimization of power system operation are shown.

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