PGU-450 network heaters modes modelling with CCGT participation in regulating the electrical load in the heating mode

E K Arakelyan¹, A V Andryushin¹, S V Mezin¹, Y Y Yagupova¹

¹ National Research University "MPEI», Moscow, 111250, Krasnokazarmennaya, 14

edik_arakelyan@inbox.ru

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

The transition of the national economy to market relations has led to certain structural changes in the electric power industry. Thus, there was a decrease in the share of industrial consumers with 2-3 shift modes of operation and a significant increase in the share of consumers with sharply alternating modes of power consumption. The absence of highly manoeuvrable units required for these modes during the passage of power consumption schedules dips led to forced deep unloading or shutdown of equipment designed for the basic operating mode. Statistics of operational modes of power plants show that even powerful power units of 300, 500 and 800 MW for supercritical steam parameters on a number of power systems during the passage of night load dips are daily unloaded up to 30-50% of the installed capacity.

The problem of heating power plants is even more complicated, because during the heating period, the passage of night dips in power consumption, as a rule, coincides with the maximum of the heat consumption schedule. Thus, at the power plants of JSC “Mosenergo”, the thermal load in the winter period at night is 80-100% of the installed thermal capacity at 30-50% of the installed electric capacity. The problem is also complicated by the fact that during the hours of dips due to the low cost

¹ edik_arakelyan@inbox.ru
of electricity on the wholesale market, its production even on thermal consumption is not economically profitable. Under these conditions, the problem of rational intra-system and intra-station operational control of the operating modes of heating power equipment becomes one of the main tasks of the automated control system at the CHPP. At the same time, it is important to use all the technical, economic and manoeuvrable advantages of the CCGT at the CHPP and take them into account when choosing the optimal equipment modes.

2. The need to take into account the actual values of underheating in network heaters
Optimization of the operating modes of power plants and equipment is traditionally one of the most difficult scientific and practical tasks, due to the uncertainty of the initial information, multivariance, difficulty in taking into account the actual technical condition of the equipment, etc. Nevertheless, at present, various models and software complexes based on them have been developed and are used in operation practice for intra-station optimization, including in the multi-criteria formulation of the problem. At the same time, as a rule, when solving this problem, as a problem of static optimization, the normative energy characteristics of individual power units are used in the form of a dependence of heat or fuel consumption on electric power, obtained at nominal initial and final steam parameters. At the same time, it is known that the real energy characteristics, especially when operating equipment at partial loads, as well as outdated equipment, can significantly differ from the standard ones, mainly in the direction of deterioration of their individual indicators [1, 2]. Thus, according to [3, 4], the underheating of mains water in mains heaters during the heating season (5-6 months) can increase by 4-5 degrees.

Studies conducted to determine the degree of influence of the underheating value on the efficiency of the T-250 power units, the results of which are given in [5], show that an increase in underheating from 5 to 10 °C leads to an increase in specific heat consumption by 1.2-1.5% for single-stage and over 2% for two-stage heating of mains water. With constant fuel consumption and constant thermal load under the same conditions, such increases in underheating lead to a decrease in the electrical power of the unit by 4-6 and more than 6 MWt, respectively.

The above data confirm the need to take into account the actual values of underheating in network heaters both with the optimal distribution of the required thermal load of the heating plant between network heaters, and with the optimal distribution of thermal and electrical loads between generating plants. Obviously, this requires a detailed analysis and modelling of technological processes in network heaters.

3. Approaches to solving the problem
There are two approaches to solving this problem:

1. Complete calculation of the thermal scheme of the CCGT power unit each time with actual (increased) underheating in network heaters and the use of the results obtained during optimization calculations. The disadvantage of this approach is that, as a rule, for its implementation, in addition to the software product, a significant amount of measured and calculated initial data is required (efficiency and parameters of the flow part of turbines, the value of steam pressure in the selections for network heaters, real values of underheating in network heaters, etc.), which require verification and refinement taking into account measurement errors.

2. The use of digital models of the power unit and the heating plant in the form of regression dependencies obtained on the basis of experimental and computational studies. Methodological approaches and algorithms for the implementation of the second approach will be considered on the example of a combined-cycle power unit PGU-450T, a simplified scheme of which is shown in Fig.1. The thermal scheme of the PGU-450T is designed in such a way as to provide any combination of electrical and thermal loads from the technical range of electrical loads and from the maximum value of the thermal load to its complete absence (condensation mode).
Let's consider the heating mode of operation of a steam turbine with partial discharge of steam into the turbine condenser.

The digital model of the CCGT is a set of regression equations showing the dependence of the output parameters of gas turbines, the heat recovery boiler, the steam turbine and the unit as a whole on the outdoor air temperature, the required electrical and thermal loads, etc. [6]. Thus, the dependence of fuel consumption on these parameters is represented as:

\[ B_f = f(t_a, N, Q, k_{mod}) \]  

(1)

Where: 
- \(B_f\) - fuel consumption, 
- \(t_a\) - outdoor air temperature, 
- \(N\) - electrical load of the unit, 
- \(Q\) - thermal load of the unit, 
- \(k_{mod}\) - a set of parameters that determine the operating mode of the CCGT.

With this representation of the consumption characteristics of the CCGT, the optimization problem can be solved directly by increasing the dimension of the problem with the inclusion of discrete parameters (mode number), but this significantly complicates the optimization algorithm and does not always lead to high efficiency of the solution.

In a simplified form, the operation of a unit with one or two gas turbines can be considered as possible modes of operation of the CCGT, since this feature has the greatest impact on the performance of the CCGT. Then the consumption characteristic will take the form:
Choosing the optimal solution under the \( n \)-th unit. When evaluating the efficiency of the heating unit (turbine) when using one CCGT unit, the criterion for changing the composition of the working equipment, since the matrix of possible operating modes of the power equipment of the station is significantly simplified.

When considering the operation of the CCGT in the condensation mode, the consumption characteristic will take the form:

\[
B_f = f(t_a, N, n_{gr}),
\]

where \( n_{gr} \) is the number of working gas turbines.

This circumstance significantly simplifies the solution of the optimization problem at the stage of choosing the composition of the working equipment, since the matrix of possible operating modes of the power equipment of the station is significantly simplified.

When approximating the calculated data with a second-order polynomial, the maximum deviations of the approximating consumption characteristics from the calculated data used do not exceed 1% for the fuel consumption of the CCGT over the entire range of load changes [7].

When the PGU-450T unit operates with one gas turbine, the characteristic has the form:

\[
B_{CCGT}(N_{CCGT}, Q_{CCGT}) = 0.216N_{CCGT} - 1.778 \times 10^{-5} N_{CCGT}^2 + 0.037Q_{CCGT} - 1.92 \times 10^{-4} Q_{CCGT}^2 + +1.214 \times 10^{-4} N_{CCGT} \cdot Q_{CCGT} + 7.322.
\]

When operating the installation with two gas turbines, the flow characteristic has the form:

\[
B_{CCGT}(N_{CCGT}, Q_{CCGT}) = 0.253N_{CCGT} - 5.084 \times 10^{-5} N_{CCGT}^2 + 0.021Q_{CCGT} - 2.72 \times 10^{-5} Q_{CCGT}^2 + 4.166 \times 10^{-5} N_{CCGT} \cdot Q_{CCGT} + 7.496.
\]

In (4) and (5) \( B_{CCGT}(N_{CCGT}, Q_{CCGT}) \) - the consumption of conventional fuel of the CCGT in tcf/h, \( N_{CCGT} \) - the electric load of the CCGT in MWt, \( Q_{CCGT} \) - the thermal load of the CCGT in MWt.

When choosing the operating modes of the heating plant at the stage of selecting the composition of the generating equipment 2-4 days before the operational ones and when carrying out the optimal distribution of heat and electric loads when preparing the station's proposals for entering the market "a day ahead", it is necessary to evaluate the efficiency of the heating unit (turbine) when using one or two-stage heating of mains water within one turbine. For this purpose, you can use a digital model of a heating plant, which is a set of material and balance equations and the dependence of fuel consumption per unit (or heat consumption per turbine) for single-stage (T1 mode) and two-stage (T2 mode) heating of mains water, taking into account the actual preheating of mains water in them:

\[
B_{T1} = a_0 + a_1 \cdot N_{T1} + a_2 \cdot Q_{T1} + a_3 \cdot N_{T1} \cdot Q_{T1} + a_4 \cdot \left(N_{T1}^2\right) + a_5 \cdot \left(Q_{T1}^2\right).
\]

\[
B_{T2} = b_0 + b_1 \cdot N_{T2} + b_2 \cdot Q_{T2} + b_3 \cdot N_{T2} \cdot Q_{T2} + b_4 \cdot \left(N_{T2}^2\right) + b_5 \cdot \left(Q_{T2}^2\right).
\]

where \( a_0, \ldots, a_5, b_0, \ldots, b_5 \) are the coefficients of the regression equation (5), respectively for single-stage and two-stage heating of mains water, obtained on the basis of the results of experimental and computational studies.

Within the limits \( Q_{unit(T1+T2)}^{min} < Q_{unit} < Q_{T1}^{max} \) (where \( Q_{unit}^{min} \) is the minimum thermal load when the unit (turbine) is operating in the T2 mode, and \( Q_{T1}^{max} \) is the maximum thermal load of the turbine in the T1 mode), the turbine can provide a given thermal load, both in the T1 mode and in the T2 mode.

When the CCGT operates in the daytime, the criterion for choosing the optimal solution under the condition \( Q_{unit} = const \) can be the maximum turbine power at \( B_{unit} = const \).
When the CCGT operates in the mode of passing the load dip according to the electric load, the minimum power of the steam turbine can serve as a criterion under the same conditions. The following algorithm for solving the problem is proposed:

- for the daytime operation of the CCGT:
  1. when \( N_{\text{unit}} \), \( Q_{\text{unit}} \) set, for one of the modes, for example, for T2, taking into account the actual underheating in the network heaters, the fuel consumption per unit is calculated:

\[
B_{\text{unit}}^{T2} = f (N_{\text{unit}}, Q_{\text{unit}}^{T2}) ;
\]

2. under the conditions \( Q_{\text{unit}}^{T2} = Q_{\text{unit}}^{T1} \) and \( B_{\text{unit}}^{T2} = B_{\text{unit}}^{T1} \) the turbine power is calculated in a single-stage mode:

\[
N_{\text{unit}}^{T1} = f (B_{\text{unit}}^{T1}, Q_{\text{unit}}^{T1}) ;
\]

It is not difficult to obtain from equation (6):

\[
N_{\text{unit}}^{T1} = a_1 + a_3 \cdot Q_{\text{unit}} + \sqrt{a_1 + a_3 \cdot Q_{\text{unit}}}^2 + \frac{B_{\text{unit}}^{T2} - a_0 - a_2 \cdot Q_{\text{unit}} - a_5 \cdot (Q_{\text{unit}})^2}{a_4} .
\]

- if \( N_{\text{unit}}^{T1} > N_{\text{unit}} \), then T1 mode is effective and vice versa.
- if \( N_{\text{unit}}^{T1} > N_{\text{unit}} \), then the T2 mode is effective and vice versa.

The proposed algorithm is based on the predicted values of thermal and electrical loads and is therefore recommended as the initial stage of solving the problem.

5. Operational optimization algorithm

When performing operational optimization during the execution of the dispatching schedule of loads, a simpler, but more accurate approach is proposed. Its algorithm includes the following steps:

1. In the steady-state operation mode of the heating plant at the specified conditions \( N_{\text{unit}} \), \( Q_{\text{unit}} \), the actual underheating in the network heaters is calculated as the difference between the saturation temperature of the selected steam by its pressure in front of the heater and the temperature of the network water behind the corresponding network heater;

2. When the heating plant is operating in the mode of two-stage heating of mains water at specified \( N_{\text{unit}} \), \( Q_{\text{unit}} \), the fuel consumption for the CCGT is calculated by the expression (4) when the CCGT is operating with one gas turbine or (5) when working with two gas turbines;

3. The network installation is switched to the mode of single-stage heating of the network water and the parameters of the selected steam are set to provide a given thermal power, for which, taking into account the underheating calculated in stage 1, the temperature and pressure of the selected steam are determined in front of the network heater and at the outlet of the steam turbine, the power of the steam turbine and the CCGT as a whole are fixed.

4. The fuel consumption is calculated as in stage 2 at \( Q_{\text{unit}} \) the new power of the CCGT, compared with the result of stage 2.

5. If the \( B_{\text{CCGTstage4}} < B_{\text{CCGTstage2}} \), then the single-stage heating mode is more effective and vice versa. It should be noted that the real value of underheating in network heaters, as in all steam-water heaters, in addition to the noted dependence on time, also depends on the value of the current water flow, in this case, on the flow of network water. Such a dependence can be obtained experimentally. In the absence of experimental data, we can use the empirical dependence [8]:

\[
u_u = \nu_u^{\text{nom}} \cdot \rho_{D}^{2.8}
\]

(11)
where \( \theta_u^{nom} \) is the underheating in the heater when the unit is operating in the nominal mode. \( \beta_0 \) is the relative flow of mains water through the heater.

6. Conclusion. Accounting for the influence of the growth of underheating of mains water on fuel consumption

Let's consider the influence of the growth of underheating of mains water behind mains heaters on fuel consumption during two-stage heating.

At the standard values of the underheating of the mains water in the heaters, the heat release \( Q \) at a given flow rate of the mains water \( G_{mw} \) will be:

\[
Q = G_{mw} \cdot c_w \cdot \left[ \left( t_{ah} - t_{bh} \right) + \left( t_{ah} - t_{ah} \right) \right],
\]

where \( c_w \) is the heat capacity of water, kcal/(kg \cdot °C), \( t_{bh}, t_{ah} \) - the temperature of the mains water before and after the mains heaters; \( t_{ah} \) - the temperature of the mains water between the mains heaters.

Taking into account the fact that \( t_{ah} = t_u - \theta_u \) and \( t_{ah} = t_u - \theta_u \) (where \( \theta_u, \theta_u \) standard values of underheating in the lower and upper heaters), we write (12) in the form:

\[
Q' = G_{mw} \cdot c_w \cdot \left[ \left( t_u - \theta_u - \Delta \theta_u - t_{ah} \right) + \left( t_u - \theta_u - \Delta \theta_u - t_{ah} \right) \right] = Q - G_{mw} \cdot c_w \cdot \left[ \Delta \theta_l + \Delta \theta_u \right].
\]

It follows from the obtained expression that in order to comply with the condition of constant heat release, it is necessary to raise the heating load for the changed underheating by an amount:

\[
\Delta Q = Q - Q = G_{mw} \cdot c_w \cdot \left( \Delta \theta_l + \Delta \theta_u \right),
\]

for this purpose, it will be necessary to increase the steam pressure in the selection to the upper mains heater by covering the regulating diaphragm, which, of course, will lead to a decrease in the electric power of the turbine. To meet the condition \( N = \text{const} \), an increase in the steam consumption per turbine by an amount will be required:

\[
\Delta D_0 = f \left( \Delta Q \right),
\]

and a corresponding increase in fuel consumption per boiler by \( \Delta B_B \).

As above, there are two fundamental approaches to calculating the value \( \Delta B_B \):

1. Complete calculation of the thermal scheme of the power unit with standard and increased underheating in network heaters and calculation of the difference in fuel consumption per unit in these variants. The disadvantage of this calculation is that, as a rule, for its implementation, in addition to the software product, a significant amount of initial data is required (the efficiency of gas turbines and waste heat boilers and the flow part of turbines, the value of real underheating in network heaters, etc.), which require clarification taking into account the real state of the equipment.

2. Using digital models of the form (7) according to the following algorithm:

- for \( \Delta \theta_u, \Delta \theta_l, G_{mw} \) we calculate the value:

\[
\Delta Q = G_{mw} \cdot c_w \cdot \left( \Delta \theta_l + \Delta \theta_u \right) \frac{1}{\eta_n},
\]

- we calculate the fuel consumption according to the dependence (7):

\[
B(N, Q') = B = f \left( N, Q + \Delta Q \right).
\]

To simplify the calculation procedure, the calculation can be carried out using the expression:

\[
\Delta B(\Delta Q) = \frac{\partial B(N, Q)}{\partial Q} \cdot \Delta Q,
\]

which, for a dependence \( B = f \left( N, Q \right) \) in the form of a second-degree polynomial, is written as:

\[
\Delta B(\Delta Q) = \left( a_2 + 2a_4 \cdot Q + a_5 \cdot N \right) \cdot \Delta Q.
\]

The disadvantage of this method is that the regression dependences of fuel consumption per unit in the form of polynomials do not always reflect the real state of the unit's equipment and require constant refinement.
The calculations carried out according to the 1st and 2nd methods show that the error of the simplified method (2) does not exceed 0.1-0.3%, however, it is easy to implement and does not require complex calculations, which is especially important for practical use.

7. References
[1] Venikov V.A., Zhuravlev V.G., Filippova G.A. Optimization of modes of power plants and power systems. Moscow: Energoatomizdat, 1990.
[2] Kudryavy V.V. Optimization of the operating modes of the CHPP equipment taking into account environmental restrictions. Bulletin of the MPEI-1996. №1. pp. 37-40.
[3] Arakelyan E.K., Burnachyan G.A., Minasyan S.A. The influence of regime factors and technical condition on the real energy characteristics of the power unit Izv. Vuzov. Energetika, 1983. №1, pp. 57-62.
[4] Gutorov V.F., Efros E.I., Simoyu L.L. Improving the efficiency of combined heat and electricity production. Energy Saving 2004, №6. pp. 64-72.
[5] Tsypulev D.Y. The choice of optimal modes of operation of thermal power plants with a complex composition of equipment. Abstract of the dissertation of the Candidate of technical Sciences. MPEI, 2007, 20 P.
[6] Khurshudyan S.R. Optimization of CCGT modes with its participation in the regulation of power and frequency in the power system (on the example of PGU-450) Abstract of the dissertation of the Candidate of Technical Sciences. MPEI, 2014, 20P.
[7] Bolonov V.O. Selection of optimal modes of power plants with CCGT Abstract of dis. candidate of Technical Sciences. MPEI, 2008, 20P.
[8] Arakelyan E. K., Burtsev S.Y. Optimization of operating modes of power engineering facilities. Lecture notes. NRU MPEI, 2018, 158P.

Acknowledgments
The study was performed with support of Russian Foundation for Basic Research, grant № 20-38-90146/20.