The method of group capacity regulation of centrifugal mechanisms is proposed to solve the problem of increasing the energy efficiency of thermal power plant auxiliaries. The method is based on using a group frequency converter for basic capacity regulation of centrifugal mechanisms. Additional regulation is commonly carried out by throttling, bypassing or changing the guide vane opening angle.

Analysis of auxiliary power consumption showed that due to ineffective regulation methods, the share of power consumption can reach 50 %.

A mathematical model of the centrifugal mechanism that allows for studying various regulation methods is developed. The task of finding optimal control parameters for a group of centrifugal mechanisms that ensure power boiler operation is stated and solved. By the results obtained, it was determined that group capacity regulation of boiler draft mechanisms is most rational. For the feed pump, an individual variable-frequency drive shall be used.

In contrast to the individual variable-frequency drive, the introduction of the group regulation method requires less investment. This method can significantly reduce the auxiliary power consumption of thermal power plants. The projected decrease in auxiliary power consumption is 10.7 %.

The results show the high efficiency of the group capacity regulation of centrifugal mechanisms, so this method can become a promising direction in increasing the energy efficiency of thermal power plants

Keywords: variable-frequency drive, group regulation, centrifugal mechanism, auxiliaries

UDC 621.311
DOI: 10.15587/1729-4061.2020.218586

ASSESMENT OF GROUP REGULATION FEASIBILITY IN THERMAL POWER PLANT AUXILIARIES CAPACITY CONTROL

V. Vanin
Doctor of Technical Sciences, Professor
Department of Higher Mathematic**
E-mail: plbvva5652xpi@gmail.com
O. Lasurenko
PhD, Associate Professor*
E-mail: lazurenkoAP@i.ua
M. Kruhol
Postgraduate Student*
E-mail: kruhgol@gmail.com
*Department of Electric Power Stations**
**National Technical University
“Kharkiv Polytechnic Institute”
Kyrpychova str., 2, Kharkiv, Ukraine, 61002

Received date 30.10.2020
Accepted date 03.12.2020
Published date 21.12.2020

1. Introduction

The energy industry is the main component of power consumption, which together with heat supply accounts for up to 70 % of fuel and power consumption. The share of world power generation at thermal power plants (TPP) is about 60 %, so high efficiency of their operation is very important. This applies to both large TPP and urban and industrial combined heat and power plants (CHP).

Major power consumers at TPP are centrifugal mechanisms (CM). CM operating modes depend on the operating modes of major plant equipment. Off-nominal operation of TPP requires regulation of the CM capacity. Most TPP use inefficient methods of CM regulation, such as throttling, bypassing and changing the guide vane opening angle. This leads to significant auxiliary power consumption. Today, the most effective method of CM capacity regulation is changing the impeller speed. For this purpose, fluid couplings or variable-frequency drive are used. The introduction of such drives is rather costly, which slows down, and sometimes makes it impossible to modernize TPP auxiliaries.

The proximity of CM operating modes and characteristics allows implementing group capacity regulation of auxiliaries. The essence of this method is that the mechanisms of the group are powered by a single common frequency converter. This converter supplies voltage with a group frequency to the common bus, thus providing basic capacity regulation of the mechanisms. Additional regulation of each of the group mechanisms is performed by existing regulation methods – changing the guide vane closing angle, throttling or bypassing.

So, one of the ways to solve the problem of improving the energy efficiency of TPP auxiliaries in conditions of limited financial resources is group capacity regulation. Investigation of CM characteristics and regulation efficiency in order to assess the feasibility of group capacity regulation determines the relevance of the given work.

2. Literature review and problem statement

Energy-saving technologies play a major role in improving energy efficiency. Outdated technologies and equipment are the reason for the inefficient operation of Ukrainian thermal power plants, which leads to significant auxiliary power consumption.

TPP operating mode is the main factor influencing the operation of the main and auxiliary equipment of the plant. Off-nominal operation of TPP units leads to a significant increase in the specific auxiliary consumption of fuel, steam and power. The paper [1] presents the main factors leading to inefficient operating modes:

- power system dispatching;
- fuel quality;

– capacity of TPP auxiliaries;

– mechanical damage of operating elements of auxiliaries and power equipment of the plant;

– high temperature of circulating water in the condenser;

– restrictions on auxiliaries;

– long-term operation of equipment without major repairs and modernization.

When modernizing TPP auxiliaries, it is necessary to introduce the latest, energy-efficient technologies. The papers [2, 3] show that the most effective method of TPP CM capacity regulation is a variable-frequency drive. However, major TPP auxiliaries have a 3–6 kV high-voltage drive. The cost of the respective frequency converters is quite high, so one possible way to solve this problem is group capacity regulation [4]. The use of such a method can be found in various industries [5–7]. In the energy sector, this method is not common, so exploring its feasibility is of considerable interest.

To assess the effectiveness of various capacity regulation methods, it is necessary to develop a mathematical model of CM. The initial data for such a model can be certificates and operating modes of equipment.

In [8], it is proposed to use similarity laws of CM to recalculate their characteristics in different operating modes. This recalculation can be used for projected power savings when implementing a variable-frequency drive compared to throttling.

But the most acceptable are mathematical models based on approximation of CM certificate characteristics [9–11]. Linearization of CM certificate characteristics [9] significantly limits the area where the mathematical model gives high accuracy of calculations. In [10, 11], a quadratic approximation of the function of one variable – capacity of the mechanism is used, but this does not allow using such models to analyze various methods of CM capacity regulation directly.

More complex mathematical models of CM are based on fundamental laws of thermodynamics [12]. The use of such models is not appropriate in the analysis of static operating modes of CM and analysis of their regulation efficiency.

Thus, mathematical models of CM based on the approximation of their certificate data require further development. The main requirement for such models is to take into account various methods of CM capacity regulation. The use of the proposed mathematical models of CM should make it possible to analyze TPP operating modes and determine the composition of the CM group for group capacity regulation. Comparing the effectiveness of various CM regulation methods will allow concluding on the feasibility of group CM capacity regulation.

3. The aim and objectives of the study

The aim of the work is to assess the feasibility of group capacity regulation of TPP auxiliaries on the example of a group of CM that ensure power boiler operation.

To achieve the aim, the following objectives are set:

– to analyze the auxiliary power consumption of TPP;

– to propose a mathematical model of the centrifugal mechanism providing for various capacity regulation methods;

– to calculate optimal control parameters for the group of centrifugal mechanisms in order to assess the feasibility of group capacity regulation of TPP CM.

4. Analysis of TPP auxiliary power consumption

The amount of TPP auxiliary power consumption is influenced by many factors, namely [1]:

– plant type;

– fuel type;

– participation of the plant in covering the power load schedule;

– plant operating mode;

– technical condition of auxiliaries.

Consider the operating mode of a typical CHP with an installed capacity of 96 MW, operating according to the thermal load schedule. CHP is made according to the steam range-type scheme. Most of thermal power goes for municipal heating and hot water supply.

Fig. 1 presents a diagram of power supply to the grid and auxiliary power consumption for 2012–2019. The initial data were obtained from the CHP automated commercial power metering system. Since CHP operates according to the thermal load schedule, the largest values of power supply fall on the winter months. In summer, power supply values are minimal, as CHP covers only the thermal load of municipal hot water supply. During 2014–2019, the operation of CHP in the summer months was limited, only the hot water peaking boiler plant operated.

As can be seen from Fig. 1, CHP operates with a low peak-load effective duration factor. CHP equipment operates in off-nominal modes, which requires regulation of the CM capacity. The use of inefficient CM regulation methods leads to high auxiliary power consumption.

Fig. 2 shows the graph of the share of auxiliary power consumption during 2012–2019. The figure shows two characteristic periods:

– winter period, when equipment operates with the maximum load, the share of auxiliary power consumption is 25–35 %;

– summer period, when equipment operates in off-nominal, and often in the minimum allowable operating modes, the share of power consumption can reach 50 %.

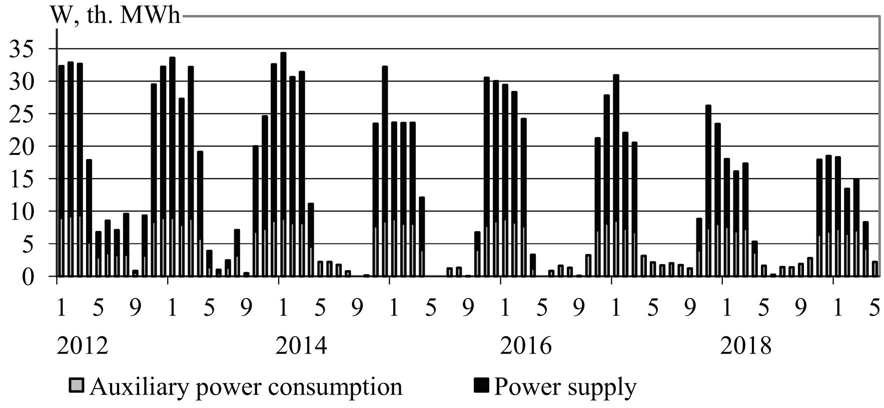


Fig. 1. Auxiliary power consumption and power supply of a typical CHP for 2012–2019

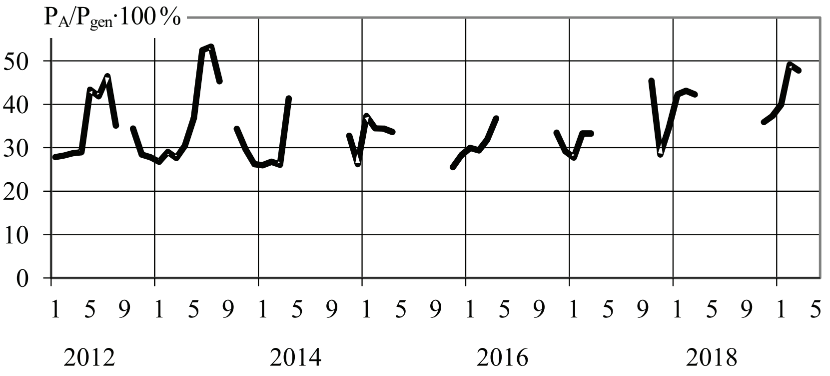


Fig. 2. Share of auxiliary power consumption of a typical CHP for 2012–2019 (months of operation of generating equipment)

The structure of CHP auxiliary power consumption is presented in Table 1. The data were obtained using the technical power metering system.

Table 1

Structure of CHP auxiliary power consumption

Consumer group	Typical winter month, %	Typical summer month, %
Thermal equipment	60.20	53.24
Feed circuit equipment	18.31	23.41
Draft equipment	15.17	14.53
Hot water peaking boiler plant	2.98	-
Chemical water treatment shop	1.52	5.50
Lighting	0.85	1.87
Other consumers	0.96	1.45

As can be seen from Table 1, a significant share of power consumption falls on thermal equipment (network pumps (NP), recirculation pumps and others), which is typical for low-capacity CHP. The plant has 14 NP with a total installed capacity of 9 MW. NP are regulated by changing the number of operating pumps and throttling. In general, CHP pumps operate in near-optimal modes, with high efficiency, so do not require the use of variable-frequency drives.

Feed circuit equipment includes feed (FP), condensate and transfer pumps. With the part-load operation of the boiler, there is a need for deep capacity regulation of its FP. At CHP under consideration, FP capacity is regulated by throttling, which leads to significant overconsumption of power. Therefore, a more appropriate solution is to introduce a variable-frequency drive.

The operating modes of the draft equipment – forced-draft fans (FDF) and induced-draft fans (IDF) also depend on power boiler operating modes. The capacity of the mechanisms of this group is regulated by changing the guide vane opening angle. This regulation method, as well as throttling, is ineffective, so there is a need to introduce a frequency-controlled drive.

Thus, one of the possible ways to improve the energy efficiency of TPP auxiliaries is the introduction of a frequency-controlled CM drive. In addition to power saving, this regulation method allows for a smooth start of CM with significant moments of inertia, limiting starting currents, increasing the drive service life.

The similarity of operating modes and characteristics of CM that ensure power boiler operation allows using group capacity regulation for these mechanisms.

5. Development of the mathematical model of centrifugal mechanism for analysis of TPP auxiliary power consumption

CM and the network it operates in form a single system characterized by the equality of flow rates and heads. Stable operation of this system is determined by the point of intersection of the head characteristic of the mechanism and the network (Fig. 3) [10, 13].

The state of the “centrifugal mechanism – network” system, the block diagram of which is shown in Fig. 4, is defined by the following parameters:

- Q – capacity of the mechanism, m^3/h;
- H – head developed by the mechanism, m;
- n – impeller speed, rpm;
- f – supply voltage frequency, Hz;
- α – guide vane opening angle, deg.

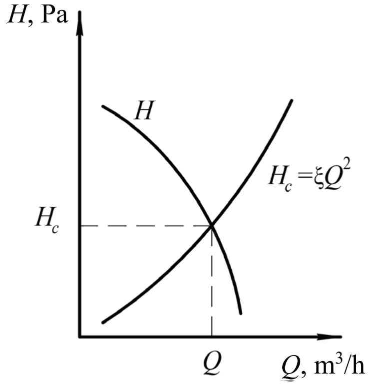


Fig. 3. Centrifugal mechanism operation in the network

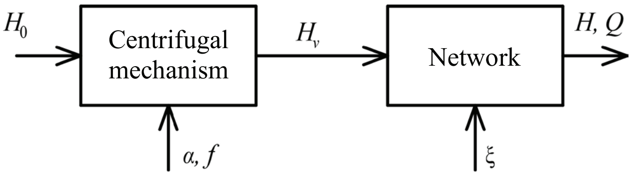


Fig. 4. Block diagram of the “centrifugal mechanism-network” system

The head developed by CM is a function of the mechanism capacity, guide vane opening angle and impeller speed

$$H = H(Q, \alpha, n), \tag{1}$$

and the head loss in the network is a function of flow friction and flow rates

$$H_n = H_n(Q, \xi). \tag{2}$$

The network characteristic (network curve) in the Q-H coordinates is chosen as a parabola [10], so expression (2) is used as

$$H_n = \xi Q^2. \tag{3}$$

We write the balance equation for the “centrifugal mechanism – network” system as

$$\Phi(\alpha,Q,n,\xi)=H(Q,\alpha,n)-H_n(Q,\xi)=0. \tag{4}$$

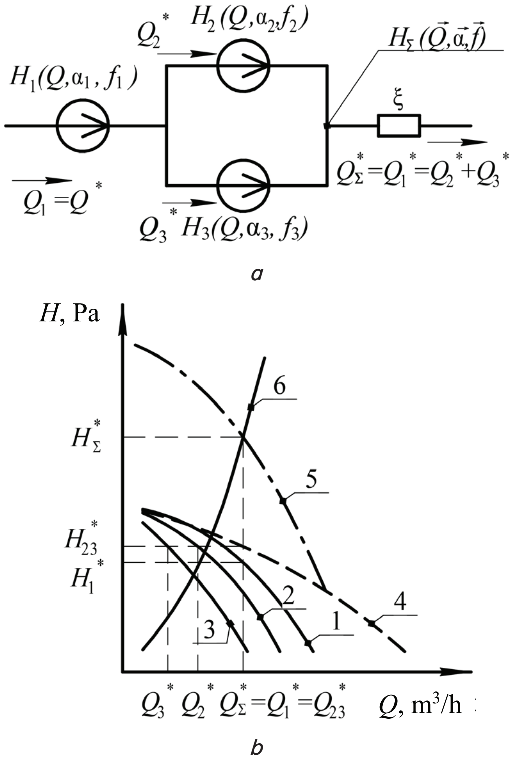
The parameter determining the CM performance is its efficiency, which depends on the mechanism capacity and its control parameters

$$\eta=\eta(Q,\alpha,n). \tag{5}$$

Most CM at TPP operate in complex branched hydraulic networks. There are three ways for CM joint operation in a network – parallel, sequential, and mixed. So, if the task is to increase the capacity of mechanisms, parallel operation is used. To increase the resulting head, CM are switched on sequentially. The paper [13] presents the algorithm for finding the equivalent characteristic of a group of centrifugal mechanisms operating on a common network. That is ensured by sequential convolution of the equivalent circuit using parallel and sequential operation of CM. The characteristic of the equivalent mechanism is

$$H=H_\Sigma\left(Q,\vec{\alpha},\vec{f}\right). \tag{6}$$

An example of constructing an equivalent characteristic of a group of CM operating on a common network is shown in Fig. 5 [13].



a

b

Fig. 5. Operation of centrifugal mechanisms with a mixed connection diagram: *a* — block diagram; *b* — equivalent characteristic construction; 1, 2, 3 — characteristics of mechanisms, 4 — equivalent characteristics of two parallel mechanisms, 5 — equivalent characteristics of a group of mechanisms, 6 — network characteristics

In the further analysis of CM operation, it is necessary to obtain relations (1) and (5). The initial data are CM certificate characteristics, often presented as graphical dependencies of heads and efficiency on CM capacity and guide vane opening angle. These characteristics can be approximated by the function of two variables as follows

$$f=c_0+c_1x+c_2y+c_3xy+c_4x^2+c_5y^2. \tag{7}$$

To determine the coefficients c_i, i=0..5, we use the least squares method [14]. For this purpose, on the basis of the initial data, tables of values $\left(a_i,Q_j,H_{ij}\right)$ and $\left(a_i,Q_j,\eta_{ij}\right)$ are taken, where $i=1\ldots N$, $j=1\ldots M$, for the nominal impeller speed of the mechanism n_0 at the supply voltage frequency f_0=50 Hz.

Taking into account (7), the restored head and efficiency functions of CM (1) and (5) are as follows

$$\tilde{H}\left(\alpha,Q,n(f_0)\right)=h_0+h_1\alpha+h_2Q+h_3\alpha Q+h_4\alpha^2+h_5Q^2, \tag{8}$$

$$\tilde{\eta}\left(\alpha,Q,n(f_0)\right)=k_0+k_1\alpha+k_2Q+k_3\alpha Q+k_4\alpha^2+k_5Q^2. \tag{9}$$

There are similarity laws for CM that allow recalculating its characteristics when the impeller speed changes [4, 10]. According to them, the mechanism capacity is proportional to the impeller speed, head – to the square of the impeller speed and power – the cube.

We use the following similarity laws

$$\frac{Q}{Q_0}=\frac{n}{n_0}, \tag{10}$$

$$\frac{\tilde{H}}{H_0}=\left(\frac{n}{n_0}\right)^2, \tag{11}$$

where Q is the actual CM capacity, m^3/h; Q_0 – nominal CM capacity, m^3/h; $\tilde{H}$ – actual head, m; H_0 – nominal head, m

For the squirrel-cage motor drive, the impeller speed depends on the supply voltage frequency in the ratio

$$n(f)=\frac{60\cdot f}{p}(1-s), \tag{12}$$

where f is the supply voltage frequency, Hz; s – slip; p – number of poles.

That is, applying (10)–(12), according to the known values of CM head and capacity at the nominal supply voltage frequency f=f_0, they can be found at other frequencies

$$Q=Q_0\left(\frac{n(f_1)}{n(f_0)}\right), \tag{13}$$

$$\tilde{H}=H_0\left(\frac{n(f_1)}{n(f_0)}\right)^2, \tag{14}$$

therefore, after mathematical transformations of expressions (8), (10)–(14), we restore (1) as

$$\tilde{H}(\alpha,Q,f)=\begin{pmatrix} h_0+h_1\alpha+h_2Q\cdot\left(\dfrac{n(f_0)}{n(f)}\right)+ \\ +h_3\alpha Q\cdot\left(\dfrac{n(f_0)}{n(f)}\right)+ \\ +h_4\alpha^2+h_5\left[Q\cdot\left(\dfrac{n(f_0)}{n(f)}\right)\right]^2 \end{pmatrix}\left(\frac{n(f)}{n(f_0)}\right)^2. \tag{15}$$

When the impeller speed changes, the efficiency remains constant for the new CM head and capacity values, i.e. the efficiency of the mechanism does not change numerically, and the efficiency curve is deformed along the Q axis. Therefore, (9) after mathematical transformations is as follows

$$\tilde{\eta}(\alpha,Q,f)=k_0+k_1\alpha+k_2Q\cdot\left(\frac{n(f_0)}{n(f)}\right)+$$
$$+k_3\alpha Q\cdot\left(\frac{n(f_0)}{n(f)}\right)+k_4\alpha^2+k_5\left[Q\cdot\left(\frac{n(f_0)}{n(f)}\right)\right]^2. \qquad (16)$$

Expressions (15), (16) can be used to calculate the stable operation of the "centrifugal mechanism – network" system and analyze various capacity regulation methods.

6. Determination of optimal CM group control parameters and assessing the feasibility of group capacity regulation

In most cases, CM operate in coordination in certain process chains, and their operating modes are interconnected. So in the task of finding optimal CM group control parameters, it is necessary to take into account the modes of their joint operation.

When analyzing the operating modes of TPP in order to increase their energy efficiency, the problem arises to find the most efficient operating mode of auxiliaries, which leads to the solution of optimal control problems. Thus, for a group of CM operating by the mixed connection scheme, the following problem can be stated [13]:

Problem. Let there be a group of N operating CM with a mixed connection with the characteristics

$$H=H_i(Q,\alpha_i,f_i),\quad i=1\ldots N,$$

operating on a network with an equivalent flow friction coefficient ξ. The total capacity of the group of mechanisms is Q_Σ^*.

It is necessary to find control parameters $\vec{\alpha}=(\alpha_1\ldots\alpha_N)$, $\vec{f}=(f_1\ldots f_N)$ for the group mechanisms, so that the weighted average efficiency of the group of mechanisms had the maximum value.

To solve this problem, it is necessary to construct (calculate) an equivalent characteristic of a group of mechanisms by equivalent transformations. We introduce the constraint function, determined by the condition of equivalent mechanism operation on the common network (4) as follows

$$\omega\left(Q_\Sigma^*,\vec{\alpha},\vec{f}\right)=H_\Sigma\left(Q,\vec{\alpha},\vec{f}\right)-H_c(Q)=0. \qquad (17)$$

Then to find the optimal control parameters, it is necessary to solve the following optimization problem

$$\left(\vec{\alpha},\vec{f}\right)=\arg\max_{\substack{\alpha\in A,\,f\in F\\ \omega\left(Q_\Sigma^*,\vec{\alpha},\vec{f}\right)=0}}\Psi\left(\vec{Q},\vec{\alpha},\vec{f}\right), \qquad (18)$$

where $\vec{Q}=(Q_1,\ldots Q_N)$ is the vector of capacity values of network CM implementing Q_Σ^*; A – range of guide vane opening angles of the group of mechanisms; F – range of supply voltage frequencies.

The objective function is defined as the weighted average efficiency of the group of mechanisms

$$\Psi\left(\vec{Q},\vec{\alpha},\vec{f}\right)=\frac{\sum_{i=1}^{N}P_i\eta_i(Q_i,\alpha_i,f_i)}{\sum_{i=1}^{N}P_i}, \qquad (19)$$

where P_i is the drive power, kW.

Let us solve the problem of optimal control of the group of MANN-120 boiler draft mechanisms. The range of boiler capacity is 60–120 t/h, superheater outlet pressure – 70 kgf/cm^2, saturated vapor temperature – 490 °C.

The block diagram of the MANN-120 power boiler is shown in Fig. 6.

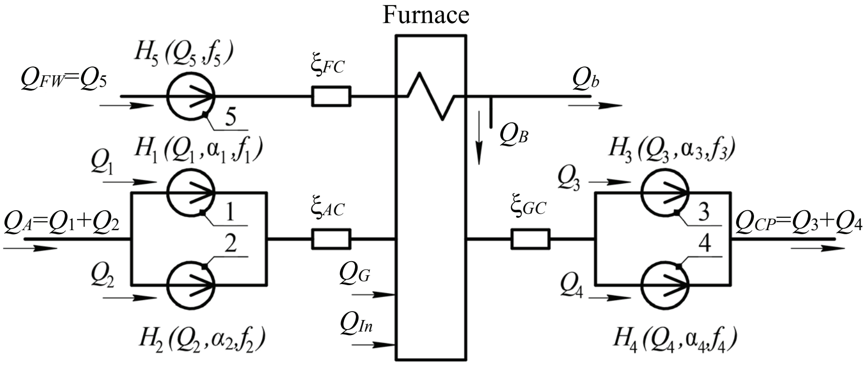


Fig. 6. Block diagram of the MANN-120 power boiler: 1, 2 — forced-draft fans; 3, 4 — induced-draft fans; 5 — feed pump; Q_A — air consumption for efficient gas combustion Q_G; Q_{CP} — consumption of combustion products formed as a result of fuel combustion and air inflows through the boiler body Q_{In}; ξ_{AC}, ξ_{GC} — equivalent flow friction of air and gas circuit parts; Q_b — boiler capacity; Q_B — blowdown feed water flow; Q_{FW} — feed water flow; ξ_{FC} — equivalent flow friction of the feed circuit; Q_i, where i=1..5 — CM capacity

Boiler operation is provided by a pair of VDN-17-3 forced-draft fans, a pair of DN-18 induced-draft fans and a Vaice-Zonne 150/100 feed pump.

Based on the certificate characteristics of centrifugal mechanisms using the least squares method, approximating expressions (15), (16) were obtained, which after mathematical transformations look like:

$$H_{1,2}(Q,\alpha,f)=0.108f^2+0.00134\alpha f^2+$$
$$+0.049\cdot10^{-3}Qf-0.0013\cdot10^{-3}\alpha Qf-$$
$$-0.00002\alpha^2f^2-0.0432\cdot10^{-6}Q^2,$$

$$\eta_{1,2}(Q,\alpha,f)=11.084+1.283\alpha+$$
$$+136.203^{-3}Qf^{-1}-1.189\cdot10^{-3}\alpha Qf^{-1}-$$
$$-0.0112\alpha^2-60.485\cdot10^{-6}Q^2f^{-2},$$

$$H_{3,4}(Q,\alpha,f)=0.0676f^2+0.00341\alpha f^2+$$
$$+0.0371\cdot10^{-3}Qf-0.0014\cdot10^{-3}\alpha Qf-$$
$$-0.000034\alpha^2f^2-0.00353\cdot10^{-6}Q^2,$$

$$\begin{aligned}&\eta_{3,4}(Q,\alpha,f)=13.027+1.647\alpha+\\&+47.895\cdot10^{-3}Qf^{-1}-0.536\cdot10^{-3}\alpha Qf^{-1}-\\&-0.0175\alpha^2-10.064\cdot10^{-6}Q^2f^{-2},\end{aligned}$$

$$H_5(Q,f)=0.0619f^2-0.0034Qf-0.0011Q^2,$$

$$\eta_5(Q,f)=2.1+59.645Qf^{-1}-15.5Q^2f^{-2}.$$

The mathematical model of the operation of the power boiler gas-air circuit is described in [15]. Extending it with the ratios for FP we obtain the following system of equations describing power boiler operation

$$\begin{cases}Q_G=c_1Q_b-c_2,\\Q_{FW}=Q_b+Q_B,\\Q_5=Q_{FW},\\Q_A=Q_gV_A^0\left(\alpha_F-\Delta\alpha_F+\Delta\alpha_{AL}\right)\times\\\times\dfrac{t_{ca}+273}{273},\\Q_A=Q_1+Q_2,\\H_5(Q_5,f_5)=H_{FC}(Q_5),\\H_{12}\left(Q_A,\vec{\alpha},\vec{f}\right)=H_{AC}(Q_A)-H_F,\\Q_{CP}=Q_G\left(V_{CP}+\Delta\alpha V_A^0\right)\times\\\times\dfrac{\vartheta_{idf}+273}{273},\\H_{34}\left(Q_{CP},\vec{\alpha},\vec{f}\right)=H_{GC}(Q_{CP})+H_F,\\Q_{CP}=Q_3+Q_4,\end{cases}\tag{20}$$

where V_A^0 – theoretically required amount of air for combustion, m^3/m^3;

α_F – excess air factor of the boiler furnace;

$\Delta\alpha_F$ – air inflows in the boiler furnace and pass;

$\Delta\alpha_{AL}$ – relative air loss in the air heater;

t_{ca} – temperature of cold air in front of the forced-draft fan, °C.

V_{CP} – volume of combustion products per 1 m^3 of fuel, m^3/m^3;

$\Delta\alpha$ – air inflows in the boiler pass and furnace;

ϑ_{idf} – temperature of combustion products (gases) in front of the induced-draft fan, °C;

$H_{AC}(Q_A)=\xi_{AC}Q_A^2$ – head characteristic of the air circuit;

$H_{GC}(Q_{CP})=\xi_{GC}Q_{CP}^2$ – head characteristic of the gas circuit;

$H_{FC}(Q_5)=\xi_{FC}Q_5^2$ – head characteristic of the feed circuit;

H_{F} – furnace draft, Pa;

ξ_{AC} – equivalent flow friction of the air circuit;

ξ_{GC} – equivalent flow friction of the gas circuit;

ξ_{FC} – equivalent flow friction of the feed circuit.

The system of equations (20) sets the required boiler capacity – Q_B. The coefficients V_A^0, α_F, $\Delta\alpha_F$, $\Delta\alpha_{AL}$, t_{ca}, V_{CP}, Q_B, $\Delta\alpha$, ϑ_{IDF}, H_F, ξ_{AC}, ξ_{GC}, ξ_{FC} are taken from the certificate, design and reference materials. Unknowns are Q_j, α_i, f_j, where i=1...4, j=1...5, which are determined when solving the optimization problem. After mathematical transformations, the system of equations (20) is as follows

$$\begin{cases}Q_5-Q_b-Q_B=0,\\H_5(Q_5,f_5)-H_{FC}(Q_5)=0,\\Q_1+Q_2-(c_1Q_b-c_2)V_A^0\times\\\times\left(\alpha_F-\Delta\alpha_F+\Delta\alpha_{AL}\right)\dfrac{t_{ca}+273}{273}=0,\\H_{12}\left(Q_1+Q_2,\begin{pmatrix}\alpha_1\\\alpha_2\end{pmatrix},\begin{pmatrix}f_1\\f_2\end{pmatrix}\right)-\\-H_{AC}(Q_1+Q_2)+H_F=0,\\Q_3+Q_4-(c_1Q_b-c_2)\left(V_{CP}+\Delta\alpha V_A^0\right)\dfrac{\vartheta_{idf}+273}{273}=0,\\H_{34}\left(Q_3+Q_4,\begin{pmatrix}\alpha_3\\\alpha_4\end{pmatrix},\begin{pmatrix}f_3\\f_4\end{pmatrix}\right)-H_{GC}(Q_3+Q_4)-H_F=0.\end{cases}\tag{21}$$

We write the system of equations (21) in vector form

$$\vec{\Omega}\left(\vec{Q},\vec{\alpha},\vec{f}\right)=0,\tag{22}$$

where

$$\vec{Q}=(Q_1,Q_2,Q_3,Q_4,Q_5);\ \vec{\alpha}=(\alpha_1,\alpha_2,\alpha_3,\alpha_4);$$

$$\vec{Q}=(f_1,f_2,f_3,f_4,f_5).$$

The problem of finding optimal control parameters for a group of centrifugal mechanisms is written as

$$\left(\vec{\alpha},\vec{f}\right)=\arg\max_{\substack{\alpha\in A,\ f\in F\\\vec{\Omega}\left(\vec{Q},\vec{\alpha},\vec{f}\right)=0}}\Psi\left(\vec{Q},\vec{\alpha},\vec{f}\right),\tag{23}$$

where

$$A=\begin{pmatrix}\alpha_1\in A_1\\\alpha_2\in A_2\\\alpha_3\in A_3\\\alpha_4\in A_4\\\alpha_5\in A_5\end{pmatrix}$$

– restrictions on guide vane opening angle,

$$F=\begin{pmatrix}f_1\in F_1\\f_2\in F_2\\f_3\in F_3\\f_4\in F_4\\f_5\in F_5\end{pmatrix}$$

– restrictions on supply voltage frequency.

The problem is solved by the targeted search method. Changing the parameters α_i, f_j, iє1..4, jє1..5, taking into account the limitations of the optimization problem (23), for which the weighted average efficiency of the group of mechanisms will be maximum.

When comparing the efficiency of various regulation methods for boiler draft mechanisms, we take into account the following features:

– in CM capacity regulation by changing the guide vane opening angle, the supply voltage frequency is fixed at the mains voltage level – 50 Hz

$$f_1 = f_2 = f_3 = f_4 = f_5 = 50\,\text{Hz=const};$$

– in group capacity regulation, the supply voltage frequency changes, but remains equal for all mechanisms

$$f_1 = f_2 = f_3 = f_4 = f_5 = f = \text{var};$$

– with the individual frequency drive, the supply voltage frequency is different for each of the mechanisms.

$$f_1 = \text{var},\ \ f_2 = \text{var},\ \ f_3 = \text{var},\ \ f_4 = \text{var},\ \ f_5 = \text{var}.$$

The problem (23) was solved for different power boiler capacities in the range of 60–120 t/h. According to the service documentation of the boiler, at its capacity of 60–85 t/h, one forced-draft fan and induced-draft fan are involved in the operation, with a capacity of 85–120 t/h – two each.

Fig. 7 presents graphs of optimal supply voltage frequencies, obtained by solving the problem (23). It can be noted that the graphs of optimal supply voltage frequencies for FDF and IDF have similar behavior, so these mechanisms can be used in group capacity regulation. The optimal frequency of FP differs significantly from those of draft mechanisms, so using FP in group capacity regulation is impossible. Fig. 7 also shows the graph of the optimal supply voltage frequency in the group capacity regulation for a group of boiler draft mechanisms.

The effectiveness of various capacity regulation methods for auxiliaries providing power boiler operation over the entire range can be estimated by the graphs of efficiency of the mechanisms presented in Fig. 8–10. As can be seen from Fig. 8, the efficiency of the individual variable-frequency drive for FP is greater with deep pump regulation. In the near-nominal operating modes of FP, the efficiency of the compared methods is almost identical.

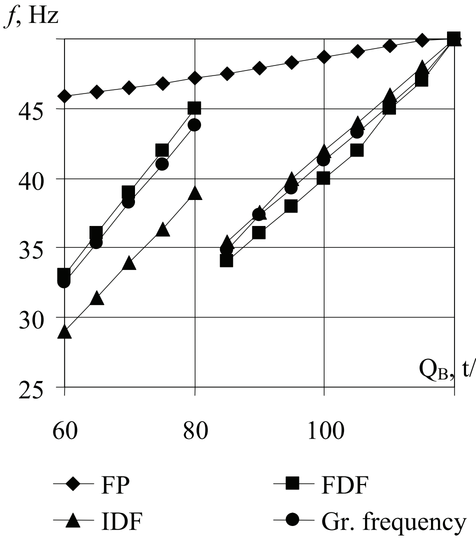


Fig. 7. Optimal supply voltage frequencies for the boiler CM

For the draft mechanisms (Fig. 9, 10), the efficiency of the individual variable-frequency drive is not much higher than that for group regulation. The least effective CM regulation method is changing the guide vane opening angle.

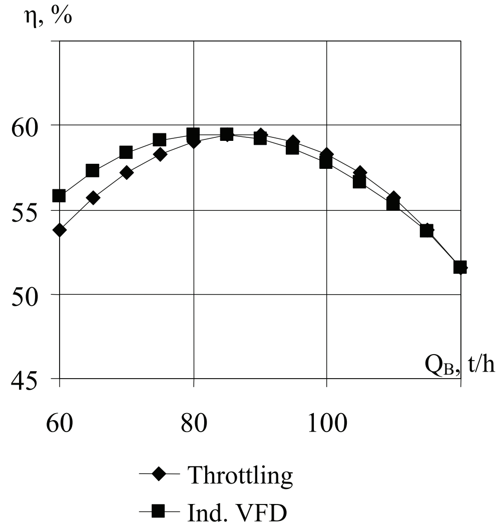


Fig. 8. Efficiency under various FP regulation methods

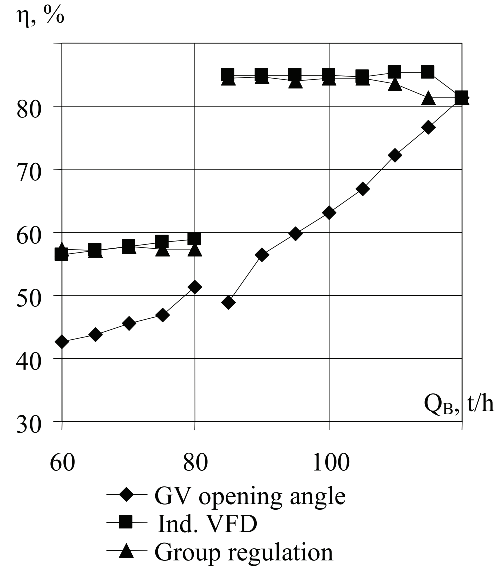


Fig. 9. Efficiency with various FDF regulation methods

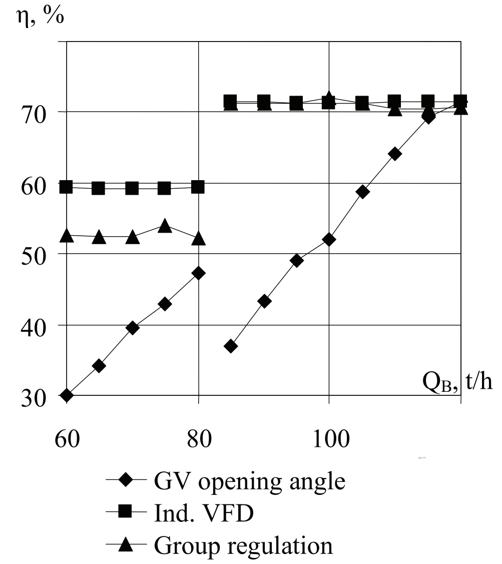


Fig. 10. Efficiency with various IDF regulation methods

Thus, group capacity regulation for boiler draft mechanisms is highly efficient and almost not inferior to the individual frequency drive, so using it at thermal power plants is promising.

7. Discussion of the results of group capacity regulation for TPP auxiliaries

The analysis of power consumption by groups of auxiliaries showed the feasibility of using the variable-frequency drive for draft equipment and feed circuit mechanisms.

The proposed mathematical model of CM can be used to study the effectiveness of various CM regulation methods. When solving the problem of finding optimal control parameters of CM providing power boiler operation (23), the dependencies of optimal CM frequencies under individual frequency regulation were obtained. The graphs of optimal frequencies (Fig. 7) allow determining the composition of a CM group for group capacity regulation.

The FP operating mode is rather specific, so it is expedient to use individual frequency converters for its drive (Fig. 7). The operation of draft mechanisms is completely determined by the power boiler operating mode. The proximity of FDF and IDF characteristics, as well as operating modes, allows implementing group capacity regulation.

Evaluation of the effectiveness of various methods of capacity regulation of auxiliaries showed that group capacity regulation for TPP auxiliaries is highly efficient and almost not inferior to the individual frequency drive (Fig. 9, 10).

The feasibility of group capacity regulation for TPP auxiliaries in contrast to other methods is due to the following:

– significant savings due to reduced investment;
– reduced size, complexity and cost of design;
– reduced engine loads;
– reduced maintenance costs;
– reduced complexity of equipment control systems.

However, the main reason for the introduction of group capacity regulation for auxiliaries is financial savings in the modernization of TPP auxiliaries.

When using one group frequency converter designed for the total power of the group mechanisms, its price is much lower than what would have been spent on the introduction of the individual frequency drive. Approximate prices or high-voltage frequency converters manufactured by Schneider Electric are shown in Table 2.

It should be noted that the introduction of group CM capacity regulation is a rather complex engineering task. Concluding on the feasibility of such a method at a particular TPP requires a thorough analysis of its operating modes, power supply diagrams of auxiliaries and equipment used. The main disadvantage of this regulation method is the difficulty of implementation for high-capacity TPP, which is due to the design features of the auxiliary switchgear. The most suitable switchgear scheme is a double-bus scheme.

Table 2

Prices for Schneider high-voltage frequency converters

Type	Power, kW	Price, USD
Schneider ATV1200-A790	500	210,000
Schneider ATV1200-A1400	1,000	320,000
Schneider ATV1200-A1750	1,350	390,000
Schneider ATV1200-A2250	2,000	425,000
Schneider ATV1200-A2910	2,200	455,000

Group capacity regulation of TPP auxiliaries is one of the promising areas of modernizing auxiliaries and can become almost the main one in conditions of limited capital. Studies show that the introduction of such a method at CHP operating on a thermal load schedule allows reducing auxiliary power consumption by 10.7 %. Future research provides for modeling dynamic and emergency operating modes of TPP equipment together with frequency converters when implementing group capacity regulation.

8. Conclusions

1. The analysis of power consumption of a typical CHP operating on a thermal load schedule showed that CHP equipment operates in off-nominal modes. The share of auxiliary power consumption is quite high and can reach 50 %. High power consumption is due to inefficient methods of capacity regulation of auxiliaries. The way out of this situation is to introduce a variable-frequency drive as one of the most effective CM capacity regulation methods.

2. The mathematical model of CM that allows for studying the effectiveness of various capacity regulation methods is proposed. This mathematical model is based on the use of the least squares method to approximate CM certificate characteristics.

3. The problem of finding optimal control parameters of the CM group, which ensure CHP power boiler operation with various capacity regulation methods, is stated and solved. It is shown that the most effective capacity regulation method is to use an individual frequency drive. Group CM capacity regulation is highly efficient and not much inferior to the individual variable-frequency drive. Therefore, given less investment in implementation, it can be a promising direction in the modernization of TPP auxiliaries. The projected decrease in CHP auxiliary power consumption is 10.7 %.

References

1. Mandi, R. P., Yaragatti, U. R. (2012). Energy efficiency improvement of auxiliary power equipment in thermal power plant through operational optimization. 2012 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES). doi: https://doi.org/10.1109/pedes.2012.6484459
2. Tamminen, J., Viholainen, J., Ahonen, T., Ahola, J., Hammo, S., Vakkilainen, E. (2013). Comparison of model-based flow rate estimation methods in frequency-converter-driven pumps and fans. Energy Efficiency, 7 (3), 493–505. doi: https://doi.org/10.1007/s12053-013-9234-6

3. Narkhede, J., Naik, S. (2016). Boiler feed pump control using variable frequency drive. International Research Journal of Engineering and Technology (IRJET), 3 (4), 2444–2449. Available at: http://www.academia.edu/download/54639146/IRJET-V3I4583.pdf
4. Kruhol, M., Lasurenko, O., Vanin, V., Tomashevskyi, R. (2019). Group Regulation Efficiency Analysis for Thermal Power Plant Auxiliaries. 2019 IEEE 6th International Conference on Energy Smart Systems (ESS). doi: https://doi.org/10.1109/ess.2019.8764242
5. Iyer, J., Tabarraee, K., Chiniforoosh, S., Jatskevich, J. (2011). An improved V/F control scheme for symmetric load sharing of multi-machine induction motor drives. 2011 24th Canadian Conference on Electrical and Computer Engineering(CCECE). doi: https://doi.org/10.1109/ccece.2011.6030711
6. Jeftenic, B., Bebic, M., Statkic, S. (2006). Controlled multi-motor drives. International Symposium on Power Electronics, Electrical Drives, Automation and Motion, 2006. SPEEDAM 2006. doi: https://doi.org/10.1109/speedam.2006.1649985
7. Mitrovic, N., Kostic, V., Petronijevic, M., Jeftenic, B. (2009). Multi-Motor Drives for Crane Application. Advances in Electrical and Computer Engineering, 9 (3), 57–62. doi: https://doi.org/10.4316/aece.2009.03011
8. Mandi, R. P., Yaragatti, U. R. (2008). Enhancing energy efficiency of Induced Draft Fans in Thermal Power Plants. Proceedings of the Eighth IASTED International Conference Power and Energy Systems (EuroPES 2008). Corfu, 176–182.
9. Kanyuk, G. I., Mezerya, A. Yu., Laptinov, I. P. (2014). A model of energy saving control using the discharge units of thermal power stations. Вісник NTU "KhPI". Seriya: Enerhetychni ta teplotekhnichni protsesy y ustatkuvannia, 12 (1055), 90–97. Available at: http://repository.kpi.kharkov.ua/bitstream/KhPI-Press/8964/1/vestnik_HPI_2014_12_Kanyuk_Model.pdf
10. Carlson, R. (2000). The correct method of calculating energy savings to justify adjustable-frequency drives on pumps. IEEE Transactions on Industry Applications, 36 (6), 1725–1733. doi: https://doi.org/10.1109/28.887227
11. Mrzljak, V., Blecich, P., Anđelić, N., Lorencin, I. (2019). Energy and Exergy Analyses of Forced Draft Fan for Marine Steam Propulsion System during Load Change. Journal of Marine Science and Engineering, 7 (11), 381. doi: https://doi.org/10.3390/jmse7110381
12. Shuping, W., Jiantao, Y., Wei, L., Xiaofeng, D., Zinian, C. (2012). Energy efficiency evaluation investigation on high voltage inverter retrofit for fans and pumps in power plants. Paris.
13. Kruhol, N., Lasurenko, O., Vanin, V. (2020). An Algebraic Model of Gas-Hydraulic Network of Mechanisms with Electric Drive in the Problem of Thermal Power Plant Auxiliaries Optimization. 2020 IEEE KhPI Week on Advanced Technology (KhPIWeek). Kharkiv, 188–192. doi: https://doi.org/10.1109/KhPIWeek51551.2020.9250085
14. Van Huffel, S., Vandewalle, J. (1991). The Total Least Squares Problem: Computational Aspects and Analysis. SIAM, 288. doi: https://doi.org/10.1137/1.9781611971002
15. Vanin, V. A., Vanin, B. V., Kruhol, M. M. (2020). Mathematical modeling of thermal power plant's boiler air-gas flow path regulation modes. Visnyk NTU "KhPI". Seriya: Matematychne modeliuvannia v tekhnitsi ta tekhnolohiyakh, 1 (1355), 8–15. Available at: http://repository.kpi.kharkov.ua/bitstream/KhPI-Press/47512/1/vestnik_KhPI_2020_1_MMTT_Vanin_Matematicheskoe.pdf