The System for Planning Cost-efficient and Resource-saving Operating Modes of TPP

Olga Chernousenko[1[0000-0002-1427-8068]], Vitalii Peshko[1*[0000-0003-0610-1403]] and Dmitro Rindyuk[1[0000-0001-7770-7547]]

[1] Igor Sikorsky Kyiv Polytechnic Institute, 37 Peremohy ave., 03056 Kyiv, Ukraine
vapeshko@gmail.com

Abstract. Thermal power plants are often operated in the semi-peak and peak part of the electrical load schedule of the power system. It is known that operation of power equipment in variable modes leads to a deterioration of economic indicators and accelerated exhaustion of residual resource. The paper proposes a system for planning rational modes of operation of power plants. The optimal distribution of the regime parameters of the power unit was investigated, namely the operating time, the number of starts and the proportion of starts from different thermal states. The target functions of the research are the specific consumption of equivalent fuel per 1 kWh of generated energy and the residual operating time of the power unit. When calculating the cost-efficiency of the power plant, it was decided to bring all types of heat, electricity and fuel losses to the similar losses of equivalent fuel. The Palmgren-Miner hypothesis was used to estimate the damage to equipment during exploitation in various operating modes. The proposed system was tested on the example of a real power unit with a capacity of 200 MW. Equipment start-up modes were investigated on the basis of start-up schedules provided by the generating company. The research results showed that using the proposed system for planning rational operating modes, it is possible to achieve a reduction of the specific consumption of equivalent fuel by 16% and an increase in the individual resource of the power unit by 21%.

Keywords: Rationalization, Exploitation Modes, Power Unit, Thermal Power Plant, Fuel Losses, Efficiency, Durability, Residual Resource.

1 Introduction

Thermal power plants (TPP) are used as semi-peak and peak capacities in the power systems of many countries around the world. This is due to the availability of cheaper energy produced at nuclear power plants, the availability of cleaner energy obtained from renewable energy sources, the insufficient supply of highly maneuverable capacities, etc. [1] The reasons for this work vary from country to country. However, the common consequence is that equipment designed to operate in stationary modes is operated in frequent variable modes [2].

The operation of any power equipment on non-stationary modes is always accompanied by deterioration of economy, environmental friendliness and reliability. This deterioration will be the more intense, the longer the duration of the variable mode and the more it differs from the nominal one [3].

At the same time, the authors of [4] note a significant impact of equipment start-up modes on the rate of damage accumulation in the base metal, which can lead to premature failure and catastrophic consequences.

Thermal power plants in many countries around the world (especially China, USA, Ukraine, Russia) are characterized by a significant exhaustion of individual resource of its equipment [5]. Therefore, the above circumstances significantly increase the relevance of rational planning of the operation of TPP units.

2 Literature review on planning cost-efficient and resource-saving operating modes of TPP

A significant amount of scientific and applied research proves the effectiveness of predictive optimization in solving problem of rational use of energy resources and reducing the negative impact of the energy sector on the environment [6, 7]. The authors of [7] showed that by optimizing the daily composition of generating equipment in the Chinese power system, it is possible to decrease material input and global warming potential by 29%, and to decrease water deprivation by 19%. The paper took into account the full cycle of energy production from the energy source to the consumer supply.

A common research is to increase the efficiency of power plants by optimizing their modes of operation [8, 9]. Thermal power plant operating on the organic Rankine cycle with a heat pump was investigated in [8]. Typical operating modes and different types of coolants for the cycle are studied. Mathematical optimization of the main thermodynamic and technological parameters of TPP was performed on the basis of exergy analysis of energy production. The optimal working parameters of the system provide a 28% increase in electrical efficiency.

The paper [9] is devoted to the study of rational modes of operation of the TPP power unit with a capacity of 300 MW. The authors investigated 7 different modes of operation of equipment from the fully basic (7000 hours per year) to the mode with daily stops for 7 hours during periods of night reduction in consumption. According to the results of calculations, an increase in the cost of electricity for the selected modes is investigated. The authors' calculations of turbine resource indicators deserve special attention. These calculations are performed using the concept of equivalent exhaustion of the resource [10] for different methods of operation. In this technique, for each damage that accumulates in the metal of the equipment due to start-up, the equivalent operating time in steady state is calculated. The data obtained by the authors are of great interest to generating companies.

At the same time, the calculations of the resource indicators of the equipment performed by the authors of [10] are somewhat simplified, as they do not take into account all the specifics of cyclic damage to the equipment during start-up. A detailed model of low-cycle fatigue of the secondary superheater of the boiler is presented in [11]. The calculations take into account the main mechanisms of destruction, as well as the effects of oxidation, corrosion and welding. When conducting a study of the optimal operating modes of the secondary superheater, it is possible to simplify the calculations of cyclic damage. For this purpose, the authors performed an analytical representation of the experimental Coffin-Manson curve for X7CrNiTi steel at a symmetrical load cycle and constant temperature.

A similar study was performed by the authors of [12]. On the basis of the modified Steinhart-Hart equation, the analytical adaptation of the fatigue curve of steel 25Cr1Mo1V at variable temperatures was performed. This analytical dependence has become a component of the system for estimating and forecasting the rational resource-saving modes of the operation of TPP. This system allows to set the distribution of the operating parameters of the unit, which will provide the least accumulation of damage during variable operating modes.

Given the above, it can be argued that research aimed at developing a system of rationalization of the operating modes of power unit to ensure cost-efficiency and resource-saving is relevant. Such a system will allow generating companies to more effectively plan the strategy of operation of their equipment. In addition, this system is important for forecasting and forming the structure of generating capacities of power systems [13]. Effective planning will significantly reduce the cost of generated electricity and prevent premature failure of the main power equipment of thermal power plants.

3 Research methodology

Rationalization of TPP operation modes in order to minimize fuel consumption requires the establishment of the value and range of changes in energy losses for typical start-up and stationary modes of operation [14].

When estimating the fuel losses during start-up ΔB_i, it is necessary to take into account not only the overconsumption of natural fuel, but also the equivalent overconsumption of fuel, which compensates losses of heat and electricity:

$$\Delta B_i = \Delta B_i^f + \Delta B_i^h + \Delta B_i^e + \Delta B_i^u \quad (1)$$

where ΔB_i^f, ΔB_i^h, ΔB_i^e – fuel, heat from an external source and electricity for own needs used on the *i* stage of start-up or cooling and reduced to the equivalent fuel (calorific value of 1 kg of equivalent fuel is equal to 29.3 MJ);

ΔB_i^u – the amount of fuel that is equivalent to the useful electricity supplied to the power grid during cooling, loading and stabilization.

It is convenient to divide the power unit start-up cycle into several stages: downtime of power unit, stage of preparation for start-up, ignition of the boiler and exploitation before the rotor rotation, acceleration of the turbine to idle frequency, electrical load of the turbine to rated power, stabilization of thermal state.

For each of the above six stages, the main components of fuel losses from the equation (1) are determined. Specific methods for calculating start-up losses are usually approved by the regulatory documents of the energy sector of the vast majority of countries [15].

Start-up operating modes of TPP power units are classified depending on the metal temperature before start-up. The determining temperature is usually the temperature of the metal of the first stage, or the flanges in the area of the steam inlet, or the steam inlet pipes.

In this paper, it is proposed to consider the following start-up modes of power units: start-up from cold state of metal (CS) at a temperature >150 ℃, start-up from uncooled state of metal (US) at a temperature 200-300 ℃ and start-up from hot state of metal (HS) at a temperature 410-460 ℃. At the same time, cold and uncooled start-ups are performed on sliding parameters of steam, which allows to significantly increase the maneuvering properties of the power unit, reduce energy losses and ensure greater uniformity of temperature fields, which has a positive effect on the stress-strain state of the main equipment.

After establishing the value of energy losses during the operation of the power unit at start-up and stationary modes of operation, it is advisable to develop a system for planning a rational strategy for the operation of thermal power plant. The main stage in the development of such a system is the formulation and solution of the optimization problem. This task is to determine the distribution of technological and operating parameters of the unit, providing minimal energy losses.

The specific consumption of equivalent fuel b_{eq} is proposed as a target function of the optimization problem. It is quite complex and easy to analyze indicator of the efficiency of electricity generation.

$$b_{eq}(\vec{x}) \rightarrow \min_{\vec{x}\in\bar{X}} b_{eq}(\vec{x}) \tag{2}$$

The solution to the set optimization problem is $\vec{x}^{opt} \in \bar{X}$, that $b_{eq}(\vec{x}^{opt}) \leq b_{eq}(\vec{x})$ for all $\vec{x} \in \bar{X}$. In other words:

$$b_{eq}(\vec{x}^{opt}) = \min_{\vec{x}\in\bar{X}} b_{eq}(\vec{x}) \tag{3}$$

$$N_{X\,min} \leq |\bar{X}| \leq N_{X\,max} \tag{4}$$

where $\vec{x}$ is vector of the operating parameters that affect b_{eq}; $\bar{X}$ is the area of the existence of $\vec{x}$; $N_{X\,min}$, $N_{X\,max}$ are the boundaries of the existence of the vector $\vec{x}$.

For the intended problem, the main components of the vector $\vec{x}$ (optimization factors) are offered to be:

1) unit operation time during the year $t_{min} \leq t_i \leq t_{max}$;

2) the total number of start-ups from different thermal states for 1 year of operation $n_{min} \leq n_j \leq n_{max}$;

3) the percentage of cold start-ups from the total number $CS_{min} \leq CS_k \leq CS_{max}$;

4) the percentage of hot start-ups from the total number $HS_{min} \leq HS_l \leq HS_{max}$.

The percentage of start-ups from the uncooled state of the metal is determined by the percentages of start-ups from other thermal states $US_{k,l} = 1 - (CS_k + HS_l)$.

Given the above, the following equation is obtained to calculate the average annual specific consumption of equivalent fuel at the TPP:

$$b_{eq\ i,j,k,l} = \frac{B_1 \cdot t_i + \Delta B_{CS} \cdot n_j \cdot CS_k + \Delta B_{HS} \cdot n_j \cdot HS_l + \Delta B_{US} \cdot n_j \cdot (1-(CS_k+HS_l))}{N \cdot (t_i - \Sigma t_{TS}) + E_{CS} \cdot n_j \cdot CS_k + E_{HS} \cdot n_j \cdot HS_l + E_{US} \cdot n_j \cdot (1-(CS_k+HS_l))} \quad (5)$$

where B_1 – absolute consumption of equivalent fuel consumed for 1 hour of operation of the power unit at rated load; $\Delta B_{CS}, \Delta B_{HS}, \Delta B_{US}$ – overconsumption of equivalent fuel at each type of start-up, calculated by equation (1); N – rated power of the power unit; E_{CS}, E_{HS}, E_{US} – the amount of energy supplied to the network for each type of start-up; t_i, n_j – term of operation and number of start-ups during the year; CS_k, HS_l – percentage of start-ups from cold and hot state of metal; Σt_{TS} – the total time spent on all start-up modes.

Thus, the numerator of the equation (5) presents the sum of all equivalent fuel consumed for all modes of operation. This value consists of the nominal consumption during the operating time t_i and the amount of fuel overconsumption at each type of start-up. The denominator shows the total amount of energy generated during the nominal and all start-up modes.

4 Rationalization of operating modes of TPP units

4.1 Minimizing fuel consumption by rationalization of operating modes

According to the nature of operation in the power system during the year, we can recognize two diametrically opposed strategies for the operation of the power unit: completely peak mode of operation and completely basic mode.

With a completely peak mode, the operating time of the unit goes to its minimum value $t_i \to t_{min}$. Conversely the number of starts goes to its maximum value $n_j \to n_{max}$. At the same time, due to the peak mode and a significant number of starts during the year, the metal of the turbine will most likely not have enough time to cool to a temperature below 150 °C (start-up from a cold state). Thus, the percentage of hot and uncooled start-ups will prevail in the share ratio $CS_k \to CS_{min}$.

With a completely basic mode of operation, the situation with the considered parameters will be opposite. Between these two exploitation strategies of the power unit there are thousands of variations with different combinations of variables t_i, n_j, CS_k, HS_l, among which there is an optimal mode surrounded by rational ones.

Given the above, the equation for calculating the average annual specific consumption of equivalent fuel (5) can be represented as:

$$b_{eq\ i,j} = \frac{B_1 \cdot t_i + n_i [CS_i \cdot \Delta B_{CS} + (1-CS_i) \cdot HS_j \cdot \Delta B_{HS} + (1-CS_i) \cdot (1-HS_j) \cdot \Delta B_{US}]}{N \cdot [t_i - \Sigma t_{i,j}^{TS}] + n_i [CS_i \cdot E_{CS} + (1-CS_i) \cdot HS_j \cdot E_{HS} + (1-CS_i) \cdot (1-HS_j) \cdot E_{US}]} \quad (6)$$

$$\Sigma t_{i,j}^{TS} = n_i [CS_i \cdot t_{CS} + (1 - CS_i) \cdot HS_j \cdot t_{HS} + (1 - CS_i) \cdot (1 - HS_j) \cdot t_{US}] \quad (7)$$

$$n_i = (n_{min} - n_{max}) \frac{t_i - t_{min}}{t_{max} - t_{min}} + n_{max} \quad (8)$$

$$CS_i = (CS_{max} - CS_{min}) \frac{t_i - t_{min}}{t_{max} - t_{min}} + CS_{min} \quad (9)$$

where t_{CS}, t_{HS}, t_{US} – duration of starts from cold, hot and uncooled states, respectively.

The practical application of the developed system for planning rational operating modes is presented on the example of a power unit with a capacity of 200 MW. The main operating parameters of the power unit are set using the start-up graphs developed by the manufacturer. The amount of electricity generated for each start-up E_{CS}, E_{HS}, E_{US} is calculated by integrating the electric power curve of the generator.

The results of the calculations are presented in Fig. 1. The boundaries of change of operating factors are chosen as follows: power unit usage time t_i = 2000-6500 h; annual number of start-ups n_i = 25-75; percentage of start-ups from the cold state CS_i = 10-90%; percentage of hot start-ups in the range of hot and uncooled start-ups GS_j = 0-100%.

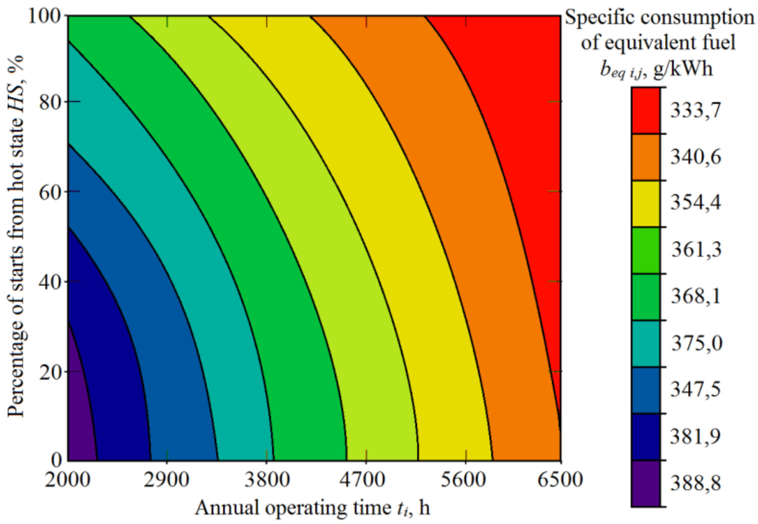

Fig. 1. The chart of specific consumption of equivalent fuel depending on operating parameters for 200 MW power unit

Analyzing the obtained results (Fig. 1), it can be noted that the rational distribution of the operating parameters of the 200 MW power unit, which are able to minimize the consumption of equivalent fuel is:

1) annual operating time of the power unit t_i = 5500-6500 h;

2) annual number of start-ups n_i = 25-36;

3) percentage of start-ups from the cold state CS_i = 72-90%, from the hot state – HS_j = 10-28%, from the uncooled state – $US_{i,j}$ = 0-18%.

When operating in this range of parameters, the consumption of equivalent fuel is about 334-340 g/kWh. The difference between the most rational and irrational regimes is 16,5% (overconsumption in 55 g/kWh).

The obtained results are expected – the optimal mode for the given boundaries of optimization parameters is the mode which is as close as possible to completely basic, at which there are no overconsumption of fuel during start-ups. The consumption of equivalent fuel in completely basic mode is b_{eq}^{bas} = 323,3 g/kWh. However, it is clear that the 200 MW unit cannot be operated in the completely basic mode of operation, both due to the operating conditions of the power system and due to accidental circumstances that could lead to an emergency shutdown of the equipment.

In addition, it should be noted that the obtained values of the specific consumption of conventional fuel are somewhat optimistic, as they are calculated for the conditions of strict implementation of start-up load graphs, instructions of exploitation and the absence of incorrect actions of operating personnel.

4.2 Ensuring the long-term operation of TPP units by rationalization operating modes

The residual resource of the power unit determines the allowable residual operating time of the equipment before the transition to the limit state. The residual operating time of a power unit is often determined by the allowable service life of its turbine and can be calculated [16]:

$$G = \frac{1 - D'_{st} - D'_c}{D''_{fc}} \tag{10}$$

where D'_{st}, D'_c are static and cyclic damage accumulated in the metal of turbine at the time of estimating residual resource; D''_{fc} – forecasted average annual damage for the next period of operation.

The calculation of damage indicators is a separate complex task, that requires a significant set of studies, performed by the authors earlier and presented in [12].

To ensure a high residual resource of the main equipment, it is proposed to rationalize the modes of operation of the power unit according to a similar approach presented above. Taking into account the Palmgren-Miner hypothesis, the residual resource of the power unit can be represented as:

$$G_{i,j} = \frac{(1 - D'_{st} - D'_c)\cdot\chi}{\frac{t_i}{[T]} + n_i\left(\frac{CS_i}{[N_{CS}]} + \frac{(1-CS_i)\cdot HS_j}{[N_{HS}]} + \frac{(1-CS_i)\cdot(1-HS_j)}{[N_{US}]}\right)} \tag{11}$$

where χ – average annual operating time of the power unit according to the technical audit; $[T]$ – allowable operating time of the metal at rated loads and maximum temperatures, determined by experimental curves of long-term strength of steel; $[N_{CS}]$, $[N_{HS}]$, $[N_{US}]$ – allowable number of start-up cycles from cold, hot and uncooled states, determined by the curves of low-cycle fatigue of Coffin-Manson [12].

Demonstration of practical use of the developed system for planning the rational operating modes of TPP power units is offered to be presented on the example of power unit № 15 of Luhansk TPP (Ukraine). Resource indicators of this unit were calculated by the authors earlier. As of 01.01.2020, this power unit has an operating time of 308 000 h with 1467 start-ups from different thermal states.

The results of rationalization of the operating modes of this power unit in order to ensure resource-saving are presented in Fig. 2.

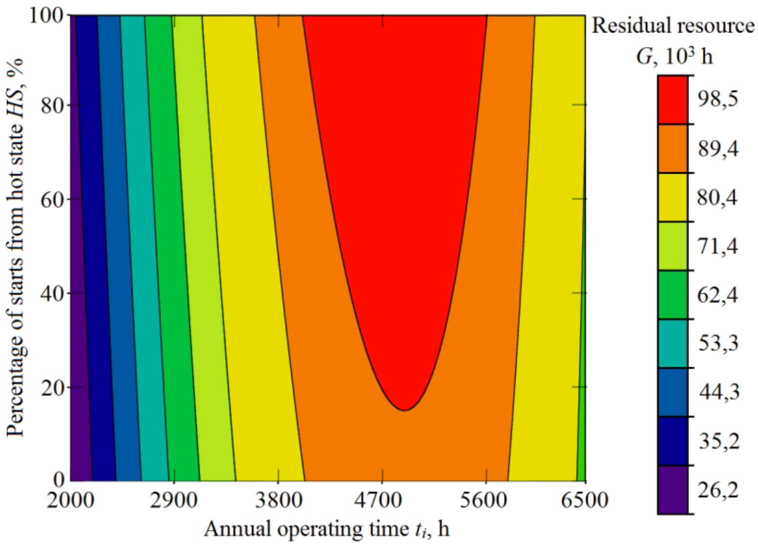

Fig. 2. The chart of residual resource of the 15th power unit of Luhansk TPP (Ukraine) depending on operating parameters

Analyzing the obtained results (Fig. 2), it should be noted that the rational distribution of the regime parameters of the 15th power unit of Luhansk TPP, which demonstrates the highest values of the residual resource is:

1) annual operating time of the power unit t_i = 4200-5300 h;
2) annual number of start-ups n_i = 38-49;
3) percentage of start-ups from the cold state CS_i = 51-68%, from the hot state –HS_j = 20-49%, from the uncooled state – $US_{i,j}$ = 0-29%.

The residual resource of the power unit is about 90-98 thousand hours when operating in this range of regime parameters.

The most rational mode of operation in comparison with irrational increases an individual resource by 21.6%. If we consider the application of this system to a new power unit that was not in operation, it is possible to achieve much higher growth rates of individual resource (up to 50%).

4.3 Discussion of research results

Considering the results of the application of the developed rationalization systems, it can be noted that the optimal distribution of the operating parameters for minimizing fuel consumption and maximizing the residual operating time, as expected, do not match. The task is to find a compromise solution that can to some extent satisfy the generating company. Therefore, we can distinguish the following distribution of the operating parameters as rational ones:

1) annual operating time of the power unit t_i = 4800-5800 h;
2) annual number of start-ups n_i = 33-44;

3) percentage of start-ups from the cold state CS_i = 60-77%, from the hot state –HS_j = 20-40%, from the uncooled state – $US_{i,j}$ = 0-20%.

When operating in this range of the exploitation parameters, the residual resource of the unit is about 87-97 thousand h at a fuel consumption of 335-346 g/kWh. This proves the effectiveness of the proposed system for planning cost-effective and resource-saving operating modes of thermal power plants.

In the future, the authors will improve the proposed system for planning rational modes of operation of TPP units, by bringing several target functions to a single one. This indicator can be considered as the economic profit of TPP from direct savings of fuel, heat and electricity, as well as the profit from extended service life, reduction of repair costs, etc. At the same time, if the profit from the direct sale of electricity to grid suppliers is taken into account, the value of the obtained results increases significantly.

In summary, it can be noted that the use of the developed system for rationalization of the operating parameters of power units is a very promising and relevant tool to improve the efficiency of TPP operation for power generating companies.

5 Conclusions

The system for planning cost-efficient and resource-saving operating modes of TPP is developed. The concept of this system is to analyze thousands of possible exploitation modes of power equipment, among which are those that provide extreme values of the selected target functions. Operating modes are determined by exploitation parameters, such as the annual operating time of the power unit, the annual number of start-ups and the percentage of start-ups from different thermal states.

The developed system for planning rational operating modes allows to increase efficiency of exploitation of thermal power plants up to 16.5%. This is achieved by reducing fuel consumption when working in irrational modes of operation. In the proposed system there is an opportunity to change the boundaries of the studied parameters.

From the point of view of resource saving when using the developed system, it is possible to significantly reduce the negative impact of irrational modes of operation on the rate of accumulation of damage in the main equipment and prevent its premature failure. As a result, the individual resource of the power unit can be increased up to 21.6%.

References

1. Zhao, X., Peng, B., Elahi, E., Zheng, C., Wan, A. Optimization of Chinese coal-fired power plants for cleaner production using Bayesian network. Journal of Cleaner Production 273, 122837 (2020). https://doi.org/10.1016/j.jclepro.2020.122837
2. Monie, S., Nilsson, A., Widén, J., Åberg, M. A residential community-level virtual power plant to balance variable renewable power generation in Sweden. Energy Conversion and Management 228, 113597 (2021). https://doi.org/10.1016/j.enconman.2020.113597

3. Milovanović Z., Papić L.R., Milovanović S., Janičić Milovanović V., Dumonjić-Milovanović S., Branković D. Planning Methods for Production Systems Development in the Energy Sector and Energy Efficiency. In: Ram M., Pham H. (eds.) Advances in Reliability Analysis and its Applications. Springer Series in Reliability Engineering. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-31375-3_3
4. Rúa, J., Verheyleweghen, A., Jäschke, J., Nord, L. Optimal scheduling of flexible thermal power plants with lifetime enhancement under uncertainty. Applied Thermal Engineering 191, 116794 (2021). https://doi.org/10.1016/j.applthermaleng.2021.116794
5. Wang, C., Song, J., Zhu, L., Zheng, W., Liu, Z., Lin, C., Peak shaving and heat supply flexibility of thermal power plants. Applied Thermal Engineering 193, 117030 (2021). https://doi.org/10.1016/j.applthermaleng.2021.117030
6. Mayanti, B., Songok, J., Helo, P. Multi-objective optimization to improve energy, economic and, environmental life cycle assessment in waste-to-energy plant. Waste Management 127, 147-157 (2021). https://doi.org/10.1016/j.wasman.2021.04.042
7. Ding, N., Pan, J., Liu, J., Yang, J. An optimization method for energy structures based on life cycle assessment and its application to the power grid in China. Journal of Environmental Management 238, 18-24 (2019). https://doi.org/10.1016/j.jenvman.2019.02.072
8. Pan, M., Lu, F., Zhu, Y., Huang, G., Yin, J., Huang, F., Chen, G., Chen, Z. Thermodynamic, exergoeconomic and multi-objective optimization analysis of new ORC and heat pump system for waste heat recovery in waste-to-energy combined heat and power plant. Energy Conversion and Management 222, 113200 (2020). https://doi.org/10.1016/j.enconman.2020.113200
9. Aminov, R., Shkret, A., Garievskii, M. Estimation of lifespan and economy parameters of steam-turbine power units in thermal power plants using varying regimes. Thermal Engineering 63, 551–557 (2016). https://doi.org/10.1134/S0040601516080012
10. Aminov, R., Garievskii, M. Effect of engagement in power and frequency control on the service life of steam-turbine power units. Power Technology and Engineering 53(4), 479–483 (2019). https://doi.org/10.1007/s10749-019-01102-z
11. Stoppato, A., Mirandola, A., Meneghetti, G., Lo Casto, E. On the operation strategy of steam power plants working at variable load: Technical and economic issues. Energy 37(1), 228-236 (2012). https://doi.org/10.1016/j.energy.2011.11.042
12. Chernousenko, O., Rindyuk, D., Peshko, V., Chernov, O., Goryazhenko, V. Development of a system for estimating and forecasting the rational resource-saving operating modes of TPP. Eastern-European Journal of Enterprise Technologies 3(8), 14–23 (2020). https://doi.org/10.15587/1729-4061.2020.204505
13. Yoshiba, F., Hanai, Yu., Watanabe, I., Shirai, H. Methodology to evaluate contribution of thermal power plant flexibility to power system stability when increasing share of renewable energies: Classification and additional fuel cost of flexible operation. Fuel 292, 120352 (2021). https://doi.org/10.1016/j.fuel.2021.120352
14. Skobalj, P., Kijevčanin, M.L., Jovanović, M., Afgan, N.H., Eric, M.A. Energy indicators impact in multi-criteria sustainability analyse of thermal power plant unit. Thermal Science 21, 1143-1151 (2017). https://doi.org/10.2298/TSCI160215178S
15. ISO 50045:2019, Technical guidelines for the evaluation of energy savings of thermal power plants, 2019-03-23, International Organization for Standardization, Geneva, Switzerland. https://www.iso.org/standard/67849.html
16. Chernousenko, O., Peshko, V. Assessment of resource parameters of the extended operation high-pressure rotor of the K-1000-60/3000 turbine. Journal of Mechanical Engineering 22(4), 41–47 (2019). https://doi.org/10.15407/pmach2019.04.041