Optimization of CCGT operating modes at variable loads taking into account equivalent operating hours

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Abstract. The optimal control of the operating modes of combined cycle power plants is a difficult scientific and practical task, due to the difficulty of taking into account the real technical condition of the equipment, the particularities of the operating modes of a combined cycle gas turbine (with one or two operating gas turbines) and other factors. To determine the optimal regime of combined cycle unit with heat recovery steam generator at variable loads, the method of calculating equivalent operating hours (equivalent operating time) was used, based on the accumulation of damageability from creep and low-cycle fatigue of the main equipment of the combined cycle unit (gas, steam turbines and heat recovery steam generators). The equivalent operating hours and economic parameters of the 450 MW combined cycle power plant were calculated and the optimal operating mode of the main equipment was determined while reducing the load during night off-peak hours.

1. Introduction
The unevenness of the electrical load schedules and the shortage of peak capacities in energy systems makes it necessary to attract power plants, which were supposed to be used in the base-load mode, to cover variable schedules of electrical loads. This task can be solved by unloading or stopping part of the equipment of operating combined cycle power plants. High efficiency, including at partial loads, and good maneuverability make combined cycle power plants indispensable for participating in the correcting of imbalances in the power systems [1]. However, although combined cycle power units have higher maneuverability than traditional steam turbines, the problem of wear of the main components from cyclic thermomechanical loads in variable modes is relevant [2, 3].

The most used are combined cycle power plants with steam turbines with a capacity of 60–150 MW, which are well combined with various gas turbines in single- and multi-shaft configurations (with one or more (up to three) gas turbines) [4]. The first powerful combined cycle power unit in Russia was commissioned at the North-Western combined heat and power plant in Saint Petersburg in December 2000. The efficiency of the power unit when operating in full condensing mode is 51%. The PGU-450T of North-West CHPP consists of the main thermomechanical equipment: two gas turbine units GTE-160 (V94.2) with turbine generators TVFG-160-2MUZ; two heat-recovery boiler P-90; one steam turbine unit with a T-150-7.7 steam turbine and TZFP-160-2MUZ generator [5, 6]. The GTE-160 gas turbine unit manufactured by Interturbo (LMZ – Siemens) under a license agreement with Siemens based on the V94.2 unit is a single-shaft turbine unit operating on a simple thermodynamic cycle, at an initial gas temperature of 1060°C and gas temperature at the turbine outlet of 535°C with an adjustable
inlet guide device. The electric power of the GTE-160 in the calculated external conditions (outside air temperature 15°C, pressure 0.1013 MPa, humidity 60%) is 153.7 MW with an efficiency of 34% [7].

2. Theoretical positions

The optimal control of the operating modes of combined cycle power plants is a difficult scientific and practical task, due to the difficulty of taking into account the real technical condition of the equipment, the particularities of the operating modes of a combined cycle power plant (with one or two working gas turbines) and other factors [8]. A convenient tool for calculating the effect of operating modes on the service life of the equipment is to use equivalent operating hours (EOHs), wherein each start-stop operation, load change and operation at each load level are assigned a number of hours in the base-load mode [9, 10]. In this case, the estimation of equivalent operating hours of individual CCGT components can be used not only to validate the periodicity of various kinds of maintenance but also for operational optimization of the combined cycle power plant [11]. The following equation is proposed to calculate the equivalent operating time $\tau_{eq}$ [12–14]:

$$\tau_{eq} = \sum_{i=1}^{N} a_i \cdot n_i + \sum_{j=1}^{Y} b_j \cdot \tau_j,$$

where $N$ is the total number of various startups or load changes; $a_i$ is the coefficient of the equivalent operation hours for i-type startup or load changes, $h$; $n_i$ is the number of i-type startups or load changes; $Y$ is the total number of operation modes; $b_j$ is the coefficient for the operation mode with j-type load; $\tau_j$ is the time of operation with j-type load, h.

The coefficient of the equivalent operation hours, which concerns low-cycle fatigue of metal, can be found for each startup type or load changes using the expression $a_i = \tau_{life} / [N]$, where $\tau_{life}$ is the established life of a steam turbine (a most critical element of a turbine – rotor), a gas turbine (blades of the first stages) or a heat recovery steam generator (superheater), determined by the technical conditions for manufacturing, h; $[N]$ is the assumed number of i-type load cycles based on the analytical curves of low-cycle fatigue. The coefficient of the equivalent operation hours, which concerns the creep properties of the metal, can be found for each mode using the equation $b_j = \tau_{life}^* / \tau_j^*$, where $\tau_j^*$ is time to rupture at j-type load, calculated using the creep rupture strength equation.

To determine the optimal regime of combined cycle power plants with waste heat boilers at variable loads, we calculate the equivalent operating hours based on the accumulation of damageability to the most loaded elements of the CCGT main equipment (gas and steam turbines and heat recovery steam generator). The thermal scheme of the combined cycle gas turbine unit PGU-450T differs from the traditional thermal schemes of steam turbine power units by the ability of the power unit to operate with different composition of operating equipment according to the technological schemes: with the full composition of the equipment (2 gas turbines + 2 heat recovery steam generators + steam turbine) and with one gas turbine turned off (1 GT + 1 HRSG + 1 ST).

Based on the results of earlier calculations for low-cycle fatigue [15], figure 1A shows the dependence of equivalent operating hours per start-stop cycle (coefficient $a_i$) on the duration of downtime preceding the corresponding start-up.

The coefficient $b_j$, taking into account the various steady-state modes of operation of a gas turbine, depends on the current temperature of the working fluid and is equal to a decrease in the service life compared to operation in the base-load mode. Figure 1B shows the dependence of the coefficient bj on the load for a gas turbine GTE-160 (V94.2), which is part of the PGU-450T [16]. In the area of high loads (from 60% to 100% of the rated power), when the variable inlet guide vanes of the compressor is involved in regulating the gas turbine unit and the temperature in front of the turbine decreases slightly (see figure 1B), the coefficient $b_j$ changes slightly (for example, the coefficient $b_j$=0.941 for 65%). In the area of low loads, the power reduction is accompanied by an intensive decrease in the temperature at the inlet and outlet of the turbine and, accordingly, the slope of the $b_j$ graph increases.
Evaluation of the decrease of reliability and economic efficiency of combined cycle power plants when operating in variable modes is of great importance for the optimization of the CCGT operation during the entire lifetime [17, 18]. The variable operating mode of the CCGT unit provides greater income in the short term, but leads to a reduction of the lifetime of the most critical components, due to thermo-mechanical fatigue loadings and, accordingly, will entail additional costs for maintenance. As the criterion of efficiency estimation, we assume the prime cost of supplied electricity $S=C/E$, where $C$ is total annual costs of electric power production, dollars/year; $E$ is annual electric power supply from the power unit, kWh/year. This parameter reflects production expenses associated with regime-based conditions of the power plant operation.

The initial data for evaluating the efficiency of a combined cycle power plant in variable modes are specific capital investment, specific fuel consumption at variable loads, fuel costs, daily operating modes, and others [16]. The unit investment in the PGU-450T was taken at 1100 USD/kW. The average discounted price of natural gas for the estimated period of 30 years is 238 USD/ton of reference fuel [19].

Figure 2 shows the results of calculations of the average forecasted prime cost of electricity for the estimated period (30 years) when operating at a constant power level in condensation mode (at an outdoor temperature of 15°C) for various compositions of operating equipment. The calculation results show that in the load range up to 50%, the operation of a combined cycle power plant with one gas turbine stopped is more economical.
Consider the variable mode of operation of the CCGT PGU-450T: 6 hours at 100% capacity and unloading at night up to 50% for 8 hours. In this case, it is possible to unload the entire power unit by 50% or to stop one gas turbine and operate half of the power unit at full capacity. When stopping one gas turbine, on the one hand, the remaining equipment is loaded more fully, and, as a result, the power unit operates with low specific fuel costs. On the other hand, additional fuel consumption will be required when starting the equipment, and an increase in the number of starts can lead to significantly higher costs associated with a decrease in the service life.

To determine the optimal regime of the PGU-450T CCGT, table 1 shows the results of calculating the equivalent operating hours and economic indicators of the CCGT with various unloading options. Although fuel costs are lower when shutdown a single gas turbine (as part of a CCGT unit) when taking into account a decrease in the service life of a gas turbine and a heat recovery steam generator due to stops and starts, the prime cost of electric power is lower by 0.18 cents/kWh (2.2%) when unloading the CCGT. Thus, it is advisable to carry out the night load reduction of the PGU-450T by unloading two gas turbines (and, accordingly, unloading the steam turbine), without stopping the gas turbine.

**Table 1. Indicators of CCGT PGU-450T with various options for unloading the power unit for the specified mode: 16 hours at 100% capacity and 8 hours (at night) 50% unloading.**

| Indicators                                                                 | Shutdown 1 GT                          | Unloading 2 GT as a part of CCGT          |
|----------------------------------------------------------------------------|----------------------------------------|------------------------------------------|
| Operating equipment                                                       | GT + HRSG + ST                         | 2 GT + 2 HRSG + ST                      |
| The number of mode changes 100%–50%–100%                                  | –                                      | 4410*                                    |
| The number of starts of GT and HRSG after 8 hours of downtime               | 2205*                                  | –                                        |
| Equivalent operating hours $\tau_{eq}$ for 15 years:                        |                                       |                                          |
| gas turbine                                                               | 129 233                                | 105 616                                  |
| steam turbine                                                             | 114 000                                | 113 300                                  |
| heat recovery steam generator                                              | 122 820                                | 113 300                                  |
| The ratio $\tau_{eq}/\tau_{life}$ for 15 years:                            |                                       |                                          |
| gas turbine                                                               | 1.292                                  | 1.056                                    |
| steam turbine                                                             | 0.570                                  | 0.567                                    |
| heat recovery steam generator                                              | 0.614                                  | 0.567                                    |
| Fuel costs, cent / kWh                                                    | 6.11                                   | 6.23                                     |
| Cost of electricity, cent / kWh                                            | 8.36                                   | 8.18                                     |
| The increase in the cost of electricity                                    | 2.2%                                   | –                                        |

* for the calculation period 30 years

Low electricity prices on the electricity and capacity market during a nightly decrease in the electrical load necessitate the operation of CCGT with deep unloading up to the lower limit of the regulation range [20–22]. Figure 3 shows the dependence of the forecast average (per day) prime cost of electric power of PGU-450T depending on the depth of night unloading. As shown in figure 3, the most efficient way to unload the PGU-450T is to unload all operating equipment, the gas turbine should only be stopped when deep unloading is performed with the required capacity of less than 112.5 MW (25%).

With a decrease in load at night off-peak time, the output power of a CCGT with two gas turbines and one steam turbine can be considerably reduced by shutting down one gas turbine with the respective heat recovery steam generator. But after the shutdown of one HRSG, the temperature of the steam pipelines near the outlet header of the superheater decreases by 150 – 200°C compared with the steam pipelines of the operating HRSG [23, 24]. The resulting thermal stresses limit the number of such modes by the fatigue failure criterion (no more than 2500 cycles). In [23], a scenario was proposed for reducing the power output of CCGT by shutting down one gas turbine and keeping the shutdown HRSG in hot reserve by supplying it with steam from the operating HRSG.
Figure 3. The prime cost of electricity (average for the calculation period) of the combined cycle unit PGU-450T in the variable mode – 16 hours at 100% capacity and 8 hours unloading at night, depending on the depth of night unloading: 1 – operation of one gas turbine; 2 – operation of two GT.

Figure 4 shows the temperature change of the metal of a superheater of a shutdown waste heat recovery steam generator heated by steam from an operating HRSG. It is seen that the steam flow rate should be more than 10 tons/h to maintain the collector temperature above 350°C, at which thermal stresses in its wall do not affect the duration of the start-up. The dependences of the equivalent operating hours for one start-up \( a_i \) on the initial steam temperature at a known metal temperature of the collector of the high-pressure superheater of the stopped recovery boiler (i.e., at starts from various thermal states) can be determined based on the data presented in figure 5 [25].

Figure 4. The dependence of the superheater temperature of the stopped heat recovery steam generator on the steam flow from the operating heat recovery steam generator [23].

Figure 5. The dependence of EOHs on the initial temperature of steam and metal header of the HRSG with a size of 426×34 mm (typical for PGU-450T): 1 – metal temperature 50°C; 2 – 100°C; 3 – 150°C; 4 – 250°C [25].

The use of part of the steam in a stopped heat recovery steam generator bypassing the steam turbine reduces the power of the CCGT. However, maintenance of the appropriate temperature of the superheater of the stopped HRSG allows you to reduce EOHs during start-up (i.e. reduce \( a_i \)), figure 6. To determine the optimal steam flow from the operating heat recovery steam generator to the stopped HRSG, the prospective prime cost of electricity CCGT (average for the calculation period) was calculated for the accepted initial data, figure 7. From figure 7 it can be seen that at 1.5% the nominal steam flow from the operating HRSG to the stopped HRSG, there will be the lowest prime cost of electricity.
Figure 6. The steam flow $G$ (relative to the nominal flow rate) required to maintain the set metal temperature of the superheater of the HRSG, and the corresponding equivalent operating hours $a_i$ when starting from this temperature state.

Figure 7. The prime cost of electricity (average for the calculation period) when the combined cycle unit PGU-450T operates for 16 hours at 100% power and 8 hours (at night) at 50% unloading, depending on the steam flow from the working to the stopped HRSG.

3. Conclusions

Based on the developed methodology, the equivalent operating hours and economic indicators of the 450 MW combined cycle power plant were calculated and the optimal operating mode of the main equipment was determined while reducing the load during night off-peak hours. It has been shown that the most efficient way of unloading a PGU-450T combined cycle power plant with two gas turbines and one steam turbine is unloading all operating equipment, the gas turbine should only be stopped when deep unloading is performed with the required capacity of less than 112.5 MW (25%). For this option of unloading the power unit when the PGU-450T is operating for 16 hours at 100% capacity and unloading for 8 hours at night up to 50%, the prime cost of electricity is 2.2% lower. With a decrease in load at night off-peak time, the output power of a CCGT with two gas turbines and one steam turbine can be considerably reduced by shutting down one gas turbine with the respective heat recovery steam generator and transferring the shutdown HRSG in hot reserve by supplying it with steam from the operating HRSG. For the combined cycle power plant PGU-450T, the optimum steam flow from the operating HRSG to the stopped HRSG is 1.5% of the nominal steam flow.

References

[1] Aminov R Z, Khrustalev V A, Shkret A F and Garievskii M V 2003 The selection of effective ways to develop electric power generation in the European part of Russia Thermal Engineering 50 332–6

[2] Mirandola A, Stoppato A and Lo Casto E 2010 Evaluation of the effects of the operation strategy of a steam power plant on the residual life of its devices Energy 35 1024–32 DOI: 10.1016/j.energy.2009.06.024

[3] Parhizkar T, Mosleh A and Roshandel R 2017 Aging based optimal scheduling framework for power plants using equivalent operating hour approach Applied Energy 205 1345–63 DOI: 10.1016/j.apenergy.2017.08.065

[4] Tsanev S V, Burov V D and Remezov A N 2009 Gas turbine and combined-cycle plants of thermal power plants (Moscow: Publishing house MEI) p 584 (in Russian)

[5] Berezinets P A, Grinenko V M, Dolinin I V, Kondrat’ev V N, Kopsov A Ya, Kostyuk R I, Ol’khovskii G G, Petrov Yu V and Radin Yu A 2011 Constructing the Russian combined-cycle cogeneration plant and mastering its operation Thermal Engineering 58 447–55 DOI: 10.1134/S0040601511060012
Radin Yu A and Davydov A V 2009 Experience in the development of combined-cycle power units PGU-450T Power stations 9 22–6 (in Russian)

Malakhov S V, Olkhovsky G G, Trushechkin V P and Khomichenko V N 2004 Thermal characteristics of gas turbine units V-94.2 operating as a part of PGU-450T at the Northwestern TPP Power stations 5 9–16 (in Russian)

Arakelyan E K, Andriushin A V, Burtsev S Y and Andriushin K A 2015 Methodology for consideration of specific features of combined-cycle plants with the optimal sharing of the thermal and the electric loads at combined heat power plants with equipment of a complex configuration Thermal Engineering 62 335–40 DOI: 10.1134/S0040601515050018

Radin Y A and Kontorovich T S 2018 Applying the equivalent operating hours principle for assignment of CCPP equipment maintenance period J. Phys.: Conf. Ser. 1111 012004 DOI: 10.1088/1742-6596/1111/1/012004

Aminov R Z, Shkret A F and Garievskii M V 2015 Calculating the Equivalent Service Lifetime of Power Generating Units in Thermal Power Plants Power Technology and Engineering 48 391–3 DOI: 10.1007/s10749-015-0540-3

Rúa J, Agromayor R, Hillestad M and Nord L O 2020 Optimal dynamic operation of natural gas combined cycles accounting for stresses in thick-walled components Applied Thermal Engineering 170 114858 DOI: 10.1016/j.applthermaleng.2019.114858

Aminov R Z, Shkret A F and Garievskii M V 2016 Estimation of lifespan and economy parameters of steam-turbine power units in thermal power plants using varying regimes Thermal Engineering 63 551–7 DOI: 10.1134/S0040601516080012

Aminov R and Garievskii M 2019 Effect of Engagement in Power and Frequency Control on the Service Life of Steam-Turbine Power Units Power Technology and Engineering 53 479–83 DOI: 10.1007/s10749-019-01102-z

Garievskii M V 2019 Evaluating the Effect of Frequency Regulation Modes on Economic Efficiency Thermal Power Plants 2019 International Multi-Conference on Industrial Engineering and Modern Technologies (FarEastCon) (Vladivostok, Russia: IEEE) DOI: 10.1109/FarEastCon.2019.8933833

Aminov R Z, Kozhevnikov A I, Yankov A V 2013 Evaluation of the influence of use modes on the development of a resource by gas turbine Proceedings of the higher educational institutions. Energy sector problems 3–4 95–100 (in Russian)

Aminov R Z and Garievskiy M V 2018 The efficiency of combined-cycle CHP plant with variable electric loads, taking into account the wear and tear of equipment Proceedings of the higher educational institutions. Energy sector problems 20 10–22 DOI: 10.30724/1998-9903-2018-20-7-8-10-22

Stoppato A, Mirandola A, Meneghetti G and Lo Casto E 2012 On the operation strategy of steam power plants working at variable load: Technical and economic issues Energy 37 228–36 DOI: 10.1016/j.energy.2011.11.042

Keatley P, Shibli A and Hewitt N J 2013 Estimating power plant start costs in cyclic operation Applied Energy 111 550–7 DOI: 10.1016/j.apenergy.2013.05.033

Aminov R Z, Shkret A F and Garievskii M V 2017 Thermal and nuclear power plants: Competitiveness in the new economic conditions Thermal Engineering 64 319–28 DOI: 10.1134/S0040601517050019

Teplov B D and Radin Yu A 2019 Improving Flexibility and Economic Efficiency of CCGT Units’ Operation in the Conditions of the Wholesale Electricity Market Thermal Engineering 66 323–30 DOI: 10.1134/S0040601519050094

Sabanin V R, Arakelyan E K, Andryushin A V and Repin A I 2018 The modern concept of the operational management of the operating modes of the equipment of the TPP New in the Russian power industry 12 6–22 (in Russian)

Arakelyan E K, Andryushin A V, Burtsev S Y and Andryushin K A 2017 Technical and economic feasibility of development innovative technological solutions for expansion the adjustment
range of high-power CCP J. Phys.: Conf. Ser. 891 012285 DOI: 10.1088/1742-6596/891/1/012285

[23] Radin Yu A, Gombolevskii V I, Smyshlyaev V B and Rudenko D V 2018 Effectiveness of Large Power Reduction for a Combined-Cycle Power Plant with Several Gas Turbines and One Steam Turbine and Some of the Shutdown Equipment Used as Hot Reserve Power Technology and Engineering 52 69–73 DOI: 10.1007/s10749-018-0911-7

[24] Radin Yu A and Kontorovich T S 2013 Selecting the initial steam temperatures in starting combined-cycle plants in compliance with the conditions of heating the high-pressure steam superheater outlet headers Thermal Engineering 60 420–5 DOI: 10.1134/S0040601513060086

[25] Radin Yu A, Kontorovich T S and Smyshlyaev V B 2018 Methodical Fundamentals for Constructing Startup Assignment Schedules for Combined-Cycle Power Plants Considering Damage Accumulation Thermal Engineering 65 702–7 DOI: 10.1134/S0040601518100063