Effectiveness of the joint scheme of steam-power and combined-cycle power units using the example of the Nevinnomyssk State Regional Thermal Power Plant

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Abstract. We attempt to solve the problem of displacing high-temperature steam bleeding in a steam turbine plant at the first regenerative heater after intermediate overheating. This can be achieved when the thermal power plant contains heterogeneous equipment, in particular, a steam turbine and combined cycle power units. The authors proposed an energy-efficient scheme for the joint operation of steam turbine unit and steam-turbine part of a combined cycle plant with the displacement of high-temperature steam onto the high-pressure feed heater (HPFH 2) using the dry steam from the medium-pressure drum of the waste boiler in order to increase the upper limit of the power plant's control range. For this research, Nevinnomyssk TPP was selected as one of the main energy facilities of the Unified Energy System of Southern Russia. We studied the joint operation of the steam turbine unit K-160-130 and the combined cycle plant CCP-410 manufactured by Siemens, Germany. We developed the methodology and calculated the energy efficiency of the new power plant operation scheme. According to the calculation results, the total increase in power amounted to 6.03 MW, while there was an increase in electrical gross efficiency by 0.64%. An assessment of the economic effect of the applied solution for the conditions of the Nevinnomyssk TPP demonstrated that the annual increase in net profit will amount to 14.47 million rubles, and the payback period of investments is 4.2 months.

1. Introduction

According to the development program of the Russian Unified Energy System for 2019 - 2025 [1], by 2025 the forecasted maximum power consumption will be about 168,983 MW. This corresponds to the average annual growth rate of maximum power consumption by 1.5%. For the South Russian UES, the projected growth rate of the load is planned to be slightly higher, which is by 2.2%. According to official data in the South Russian UES [2] for December 2019, the electricity generation amounted up to 9 048 GW/h, and the energy consumption is 9 361 GW/h. This indicates a continuing imbalance, as well as the potential for using new capacities or increasing the maximum load at the operating facilities. Despite the active development of renewable energy sources [3] and research in the field of distributed generation in Russia [4, 5], thermal power plants still play a key role in this field (as of December 1, 2019, they take 67% from all the installed capacity of power plants in Russian UES) [6].

To obtain additional peak electrical power at steam turbine power plants, various solutions can be used. One of them is to turn off regenerative high-pressure heaters or bypass them by the feed water. This method is aimed at limiting the flow of steam into the regeneration system and increasing its flow...
into the flow part of the turbine, which leads to an increase in its power. Depending on the type of installed turbines and steam parameters, the bypassing of the HPFH of steam-powered plants by the feed water gives a power increase by up to 12% [7, 8]. When the HPFH is turned off, an increase in the turbine power occurs with an increase in the specific heat consumption. This happens due to the reduced enthalpy of feed water, while the internal turbine efficiency decreases and the vacuum in the condenser deteriorates. In addition, the systematic shutdown of the HPFH can lead to low-cycle metal fatigue in feed pipelines and heaters.

To eliminate the above-mentioned negative effects of this method, a number of researchers proposed not to use a shutdown of the HPFH but a substitution by steam bleedings from other available sources. Such steam sources can be waste heat boilers of built-in gas-turbine units [9, 10]. When installing various types of steam turbine units at the station, one can use schemes for joint operation of steam turbine units with the replacement of high-temperature steam by low-temperature one of required pressure in order to increase power, increase reliability and efficiency [11 - 14].

Studies aimed at increasing the mobility of coal-fired TPPs have become a separate direction in the global energy sector. This is carried out due to the complete shutdown of the HPFH and heating of feed water using solar water heaters installed alongside the HPFH [15 - 17].

In this work, it is proposed to use steam from a waste heat boiler of a combined cycle gas turbine as a steam source to replace the steam bleeding for the HPFH.

2. Research object description

For our research, Nevinnomyssk TPP was chosen. It is a state power plant, one of the main energy facilities of the South Russian UES. It is located in the city of Nevinnomyssk, Stavropol Territory, North Caucasus Federal District.

The block part of the Nevinnomyssk TPP is equipped with five K-155-130 power units and one K-160-130 unit, produced by Kharkiv Turbine Plant, with gas-oil boiler units TGM-94. A distinctive feature of the thermal circuit of these power units is the fact that the manufacturer recommended damping regenerative steam bleeding no. 2, which is located first along the steam stream in the turbine flow section after an intermediate superheater. The disconnection of this bleeding is connected with the burning of the inlet steam pipes of HPFH 2 by high-temperature steam. It is recommended to use steam from the first unregulated bleeding as a heating medium in HPFH 2. The parameters of the steam from regenerative bleedings for the HPFH are shown in table 1.

| Bleeding purpose | Steam parameters in the bleedings | Feed water |
|------------------|----------------------------------|------------|
|                  | $P_s$, MPa | $t_s$, °C | $t_k$, °C | $D$, kg/s | $t_{f_w}$, °C |
| HPFH 3           | 3.14      | 375      | 237.1    | 2.47     | 228.4       |
| HPFH 2           | 3.14      | 375      | 237.1    | 10.15    | 218.5       |
| HPFH 1           | 1.23      | 451      | 189.1    | 3.83     | 179.9       |

In 2011 CCP-410, a three-circuit binary combined cycle gas turbine unit was introduced. It consists of a gas turbine SCC5-4000F, a steam turbine SST-900/700 DRH manufactured by Siemens and a recovery manufactured by CMI company. The main performance indicators of the latter are shown in table 2. The distinctive features of CCP-410 of the Nevinnomyssk TPP are the connection of high-pressure cylinder (HPC) and low-pressure cylinder (LPC) with an electric generator through a pressure reducer. It also has an intermediate overheating of the combined steam flow from the medium pressure circuit and after the HPC.

The distance between the combined cycle plant and the unit at Nevinnomyssk TPP is about 250 m (figure 1).
Table 2. Key performance indicators for the CMI recovery boiler.

| Name of the parameter                                      | Unit of measurement | Value  |
|------------------------------------------------------------|---------------------|--------|
| The consumption of combustion products                     | m³/h                | 2157465|
| The temperature of the combustion products in front of the waste boiler (WB) | °C                  | 593.6  |
| The temperature of the combustion products beyond the WB   | °C                  | 94.36  |
| The gross efficiency of the waste boiler                   | %                   | 89.49  |
| The consumption of high pressure (HP) feed water at WB     | kg/s                | 64.23  |
| The vapor pressure in the HP drum                          | MPa                 | 10.316 |
| The HP steam pressure beyond the WB                        | MPa                 | 10.03  |
| The HP steam temperature beyond the WB                      | °C                  | 549.2  |
| The HP steam consumption beyond the WB                      | kg/s                | 62.4   |
| The medium-pressure (MP) feedwater consumption for WB      | kg/s                | 13.73  |
| The steam pressure in MP drum                               | MPa                 | 2.547  |
| The MP steam pressure behind the superheater               | MPa                 | 2.41   |
| The MP steam temperature beyond an intermediate superheater| °C                  | 547.6  |
| The steam consumption at the outlet to the intermediate superheater | kg/s               | 74.69  |
| The MP steam consumption beyond the WB                      | kg/s                | 10.8   |
| The steam pressure in the low pressure (LP) drum            | MPa                 | 0.446  |
| The LP steam pressure beyond the WB                         | MPa                 | 0.43   |
| The LP steam temperature beyond the WB                      | °C                  | 291.9  |
| The LP steam consumption beyond the WB                      | kg/s                | 11.0   |
| The consumption of the main condensate on a gas condensate heater | kg/s              | 88.8   |

Figure 1. Satellite image of the Nevinnomyssk TPP: 1 - Steam-turbine power units K-155-130 and K-160-130, 2 - Combined-cycle plant CCP-410.

3. Proposed solution
The layout and composition of the equipment of the Nevinnomyssk TPP allow applying the scheme of joint operation of the turbine units of the steam power unit K-160-130 and the steam turbine part of the combined cycle plant CCP-410 with the displacement of high-temperature steam bleeding to the regenerative high-pressure steam boiler from the recovery boiler [18, 19]. It is shown in figure 2.
In this scheme, steam is displaced from the first regenerative bleeding of the turbine going to HPFH 2, with steam from the medium-pressure drum of the waste boiler CCP-410. To maintain mass balance, condensate is returned from the K-160-130 condenser to the combined-cycle unit.

Figure 2. Schematic diagram of the joint operation of the steam turbine unit K-160-130 and combined cycle plant CC3-410 of the Nevinnomyssk state thermal power station:
1 – steam boiler; 2 – boiler superheater; 3 – steam turbine high pressure cylinder; 4 – steam turbine power generator; 5 – steam superheater; 6 – the third high pressure heater; 7 – the first high-pressure heater; 8 – deaerator; 9 – group of low pressure heaters; 10 – low pressure cylinder of steam turbine unit; 11 – condenser of the steam turbine unit; 12 – condensate electric pump of steam turbine unit; 13 – power electric pump of steam turbine unit; 14 – the second high pressure heater; 15 – medium pressure drum; 16 – condensate pump of a combined cycle gas unit; 17 – compressor; 18 – combustion chamber; 19 – gas turbine; 20 – the first electric generator of a combined cycle gas unit; 21 – waste boiler; 22 – high pressure superheater; 23 – high pressure evaporator; 24 – high-pressure cylinder of a combined-cycle gas unit; 25 – the second electric generator of the steam-gas block; 26 – medium-pressure superheater; 27 – high pressure drum; 28 – medium pressure evaporator; 29 – medium pressure cylinder of a combined cycle gas turbine unit; 30 – low pressure superheater; 31 – high pressure economizer; 32 – medium pressure economizer; 33 – low pressure evaporator; 34 – gas condensate heater; 35 – low-pressure drum with integrated deaerator; 36 – medium-pressure feed electric pump of a combined cycle gas turbine unit; 37 – high-pressure feed electric pump of a combined-cycle gas unit; 38 – low pressure cylinder of vapor-gas block; 39 – condenser of combined-cycle gas unit.
4. Methodology and results of thermodynamic efficiency calculation

The calculation is made under the following assumptions:

— the calculation is carried out at rated power, condensation mode, unnamed fuel consumption and outdoor temperature +15 °C;
— the relative internal turbine efficiency is assumed to be constant;
— the effect of changes in steam flow rate on its parameters in the flow part of the turbines is not taken into account;
— the effect of changes in steam flow on the vacuum in condensers is not taken into account;
— steam losses in the cycle and boiler blowdown are not taken into account;
— the influence of changes in the flow rates of the main and secondary condensate, feed water for steam flow rate on the other regenerative heaters (except for HPFH 1, 2 and 3) are not taken into account.

When using the scheme of joint work of the steam turbine block K-160-130 and the combined cycle gas turbine unit CCP-410, the steam that was used to heat the feed water in HPFH 2 will remain in the flow part of the turbine. Due to the fact that there are restrictions on the steam flow from the middle-pressure drum of the CCP waste boiler and the steam has a lower pressure than the displaced one (Table 1), the temperature of the feed water after HPFH 2 will decrease. This will lead to an increase in the consumption of heating steam from the first bleeding for HPFH 3 for reheating feed water in front of the boiler.

The increase in the consumption of heating steam from the first bleeding for HPFH 3, kg/s:

$$\Delta D_1 = \frac{G_{FW} \cdot C_p \cdot \Delta t_{FW,UND,HPFH2}}{i_{HPFH3} - t_{C,HPFH3} \cdot C_p},$$  \hspace{1cm} (1)

where $G_{FW}$ – the feed water consumption, $G_{FW} = 135$ kg/s (487 t/h);
$C_p$ – the water heat capacity, $\text{kJ/kg}^\circ\text{C}$;
$i_{HPFH3}$ – the enthalpy of the steam from the first regenerative bleeding of CTP aimed for HPFH heating 3, kJ/kg;
$t_{C,HPFH3}$ – the steam condensate temperature from the first regenerative bleeding of CCP aimed for HPFH 3 heating, °C;
$\Delta t_{FW,UND,HPFH2}$ – the value of feed water underheating in HPFH 2 when it is heated by steam from a CCGT medium-pressure drum, °C:

$$\Delta t_{FW,UND,HPFH2} = t_{FW,HPFH2} - t_{RW,HPFH2},$$  \hspace{1cm} (2)

where $t_{FW,HPFH2}$ – the feed water temperature after HPFH 2 when it is heated with steam from CTP regenerative bleeding, $t_{FW,HPFH2} = 218.5$ °C;
$t_{RW,HPFH2}$ – the feed water temperature after HPFH 2 when it is heated by steam from a CCP medium-pressure drum, °C:

$$t_{RW,HPFH2} = t_{RW,HPFH1} + \frac{D_{MP} \cdot (i_{MP} - C_p \cdot t_{C,MP}) + D_{HPFH3} \cdot C_p \cdot (t_{C,HPFH3} - t_{C,MP})}{G_{FW} \cdot C_p},$$  \hspace{1cm} (3)

where $D_{HPFH3}$ – the consumption of the heating steam from the regenerative bleeding of STP aimed for heating HPFH 3 before reconstruction, kg/s;
$i_{MP}$ – the vapor enthalpy at the outlet of the CCP medium-pressure drum, kJ/kg;
$t_{C,MP}$ – the steam condensate temperature from a CCP medium-pressure drum, $t_{C,MP} = 224.9$ °C;
$D_{MP}$ – the steam consumption of a medium-pressure CCP drum, kg/s (the maximum allowable flow rate for Nevinnomyssk TPP is 10.8 kg/s);
$t_{FW,HPFH1}$ – the feed water temperature after HPFH 1, $t_{FW,HPFH1} = 179.9$ °C.

To assess the power gain in a steam turbine installation, it is necessary to determine the heat drop acquired in the superheater or to recalculate the enthalpy of steam after overheating. In the calculation,
we take into account that the thermal power of the intermediate superheater does not depend on the steam consumption in it.

Steam consumption in the superheater before reconstruction, kg/s:

\[ D_{S,SH} = G_{FW} - D_{HPFH2} - D_{HPFH3}, \]  

(4)

where \( D_{HPFH2} \) – the consumption of heating steam from the regenerative bleeding of STP aimed into HPFH 2 for heating before reconstruction, kg/s.

The heat transfer acquired in the superheater before reconstruction, kJ/kg:

\[ \Delta i_{SSH} = i_{SSH} - i_{HPFH3}, \]  

(5)

where \( i_{SSH} \) – the steam enthalpy after an intermediate superheater before the reconstruction, kJ/kg.

The thermal power of a reheater, kW:

\[ Q_{SSH} = D_{SSH} \cdot \Delta i_{SSH}. \]  

(6)

The steam consumption in the reheater after reconstruction, kg/s:

\[ D_{SSH}^{NEW} = G_{FW} - D_{HPFH3} - \Delta D. \]  

(7)

The heat drop acquired by a reheater after reconstruction, kJ/kg:

\[ \Delta i_{SSH}^{AFTER} = \frac{Q_{SSH}}{D_{SSH}^{NEW}}. \]  

(8)

The total increase in power of the steam turbine block after reconstruction, MW:

\[ \Delta N_{STP} = \Delta N_{HPFH2} - \Delta N_{HPFH1}, \]  

(9)

where \( \Delta N_{HPFH2} \) – the additional power received by the steam flow released during the replacement of the steam that went to HPFH 2 taking into account the loss of power for heating the feed water in HPFH 3, MW:

\[ \Delta N_{HPFH2} = (D_{HPFH2} - \Delta D) \cdot (i_{HPFH2} + \Delta i_{SSH}^{AFTER} - i_{C,STP}) \cdot 10^{-3} \cdot \eta_{M,STP} \cdot \eta_{E,STP}, \]  

(10)

where \( D_{HPFH2} \) – the steam consumption going to HPFH 2 when it is heated by steam from the regenerative bleeder, kg/s;

\( i_{HPFH2} \) – the steam enthalpy going to HPFH 2 when it is heated by steam from the regenerative STP bleeding, kJ/kg;

\( i_{C,STP} \) – the steam enthalpy at the exit of the K-160-130 turbine, kJ/kg;

\( \eta_{M,STP} \) – the mechanical efficiency of K-160-130, \( \eta_{M,STP} = 0.99 \); \n
\( \eta_{E,STP} \) – the electrical efficiency of K-160-130, \( \eta_{E,STP} = 0.98 \).

\( \Delta N_{HPFH1} \) – the STP power loss after reconstruction due to additional steam consumption from the third steam bleeding extraction at HPFH 1 for feed water reheating, MW:

\[ \Delta N_{HPFH1} = \Delta D_{3} \cdot (i_{HPFH1} - i_{C,STP}) \cdot 10^{-3} \cdot \eta_{M,STP} \cdot \eta_{E,STP}, \]  

(11)

where \( i_{HPFH1} \) – the steam enthalpy going to HPFH 1 when it is heated by steam from the regenerative STP bleeding, kJ/kg;

\( \Delta D_{3} \) – the additional consumption of heating steam from the third bleeding on HPFH 1, kg/s:

\[ \Delta D_{3} = D_{HPFH1}^{NEW} - D_{HPFH1}; \]  

(12)

where \( D_{HPFH1} \) – the steam consumption going to HPFH 1 when it is heated by steam from the regenerative STP bleeding, kg/s;

\( D_{HPFH1}^{NEW} \) – the steam consumption going to HPFH 1 when it is heated by steam from the regenerative STP bleeding after the reconstruction, kg/s:

\[ D_{HPFH1}^{NEW} = \frac{G_{FW} \cdot C_{p} \cdot (t_{FW,HPFH1} - t_{FW,3}) \cdot (D_{HPFH3} + \Delta D) \cdot C_{p} \cdot (t_{C,SD} - t_{C,HPFH1})}{i_{HPFH1} - t_{C,HPFH1} \cdot C_{p}}, \]  

(13)
where $t_{FW,D}$ – the feed water temperature exiting the deaerator, $t_{FW,D} = 158$ °C;

$t_{CHPFH1}$ – the steam condensate temperature from the third regenerative STP bleeding going for heating into HPFH 1, °C;

$i_{HPFH1}$ – the steam enthalpy from the third regenerative STP bleeding going for heating into HPFH 1, kJ/kg.

The power loss in a combined cycle gas turbine unit will depend on a decrease in the steam flow entering the medium-pressure cylinder.

$$\Delta N_{CCP} = D_{MP} \cdot (i_{MP} - i_{C,CCP}) \cdot 10^{-3} \cdot \eta_{M,CCP} \cdot \eta_{E,CCP},$$

(14)

where $i_{C,CCP}$ – the steam enthalpy at the exit of the steam turbine of the combined cycle plant, kJ/kg;

$\eta_{M,CCP}$ – the mechanical efficiency of the CCP steam turbine, $\eta_{M,CCP} = 0.99$;

$\eta_{E,CCP}$ – the electric efficiency of the CCP steam turbine, $\eta_{E,CCP} = 0.98$.

The total increase in power from the application of a joint scheme, MW:

$$\Delta N_{SUMM} = \Delta N_{STP} - \Delta N_{CCP}.\quad (15)$$

The results of the study are presented in table 3.

**Table 3.** The results of the study of the joint operation scheme of the steam turbine block K-160-130 and combined cycle plant CCP-410 of the Nevinnomyssk TPP.

| Parameter                                                                 | Value   |
|---------------------------------------------------------------------------|---------|
| The reduction of steam flow from the first bleeding of K-160-130 turbine for regenerative heating of feed water, t/h | 33.4    |
| The increase in steam consumption from the third bleeding of the turbine K-160-130 for regenerative heating of feed water in HPFH 1, t/h | 0.58    |
| Reducing the steam flow entering the CCP medium-pressure superheater, t/h | 38.9    |
| The change in power while reducing the consumption of heating steam in the first STP bleeding, MW | + 10.344 |
| The change in power with increasing consumption of heating steam in the third STP bleeding, MW | - 0.156 |
| The change in power of a combined cycle gas turbine unit, MW | - 4.161 |
| The total power increase, MW | 6.027   |

Studies of the joint operation scheme of the K-160-130 steam turbine unit and the combined cycle gas turbine unit CCP-410 of the Nevinnomyssk District Thermal Power Station were carried out under the nominal mode and constant fuel consumption and demonstrated that the use of the joint operation scheme allows obtaining additional power without reducing the efficiency of the power plant, as it happens the case with the simple shutdown of the HPFH.

The increase in the average electrical gross efficiency of the block K-160-130 and CCP-410 after reconstruction will be:

$$\eta_{AVE} = \frac{\Delta N_{SUMM}}{Q_{P}^H (B_{STP}^{NOM} + B_{CCP}^{NOM})} \cdot 100,$$

(16)

where $Q_{P}^H$ – the fuel calorific power, MJ/m³, $Q_{P}^H = 34.1$ MJ/m³;

$B_{STP}^{NOM}$ – the nominal fuel consumption of the block K-160-130, $B_{STP}^{NOM} = 11.61$ nm³/s (41800 nm³/h);

$B_{CCP}^{NOM}$ – the rated fuel consumption of CCP-410, $B_{CCP}^{NOM} = 16.21$ nm³/s (58370 m³/h).

$$\eta_{AVE} = \frac{6.027}{34.1(11.61+16.21)} \cdot 100 = 0.64\%.$$
5. Methodology and results of calculating the economic effect

To assess the economic effect of the joint scheme, we accept the following assumptions and initial data:

─ reconstruction involves laying steam and condensate pipelines 300 m long;
─ the bleeding for HPFH 2 will be carried out only during the operation period at a technical maximum (average 6 h/day for a year). Additionally generated electricity will be fully sold;
─ the increase in electric capacity will not be taken into account when calculating payments for installed capacity;
─ operating costs remain constant;
─ according to the data specified in order no. 1625/19 dated 12.12.2019 of the Federal Antimonopoly Service, in the first quarter of 2020, for Nevinnomyssk TPP, the tariff rate for electric energy supplied by steam turbine units is 1274.21 rubles / (MW·h); energy sold by a combined-cycle plant is 1096.13 rubles / (MW·h).

According to preliminary estimates, the cost of implementing the joint operation scheme of the K-160-130 and CCP-410 units is 5.1 million rubles, from which 2.9 million rubles are the cost of materials and 2.2 million rubles are the cost of work.

The calculation was carried out according to WD 53-34.1-09.321-2002. “Methodology for rapid assessment of the economic efficiency of energy-saving measures at thermal power plants”. We used the simple criteria of economic efficiency, i.e. without taking into account the time factor. The results of an express assessment of the economic effectiveness of the proposed solution are shown in table 4.

Table 4. The results of calculating the economic effect.

| Parameter                                             | Value   |
|-------------------------------------------------------|---------|
| The annual increase in electricity supply from K-160-130 mln kW * h/year | 22.31 |
| The annual decrease in electricity supply from CCP-410 mln kW * h/year | 9.11 |
| The growth in retained earnings from increased sales, mln rubles/year | 18.44 |
| The income tax increase, mln rubles/year | 3.69 |
| The increase in depreciation, mln rubles/year | 0.28 |
| The increase in operating costs, mln rubles/year | 0 |
| The annual increase in net profit, mln rubles/year | 14.47 |
| The payback period, years | 0.35 |

6. Conclusion

The study showed the effectiveness of joint operation scheme of a steam power unit and a combined cycle plant during the period of technical maximum. So, in the conditions of the Nevinnomyssk TPP, the displacement of high-temperature steam bleeding unit onto the high-pressure regenerative heater (HPFH 2) of the K-160-130 steam turbine unit with dry steam from the medium-pressure drum of the CCP-410 waste boiler allows increasing the maximum electric power of the power plant by 6.03 MW at a slight increase in total electrical efficiency.

The application of the joint scheme in the conditions of the Nevinnomyssk TPP is economically justified. Its implementation will lead to an increase in annual net profit by 14.47 million rubles, with a payback period of investment - 4.2 months.

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Reference

[1] Order of the Ministry of Energy dd 02.02.2019 N 174 “On approval of the development scheme and program for Russian Unified Energy System for 2019-2025” https://www.so-
