Evaluation of the efficiency of thermal power plants in variable modes taking into account equipment wear

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Abstract. A significant share of nuclear generation in total electricity production, an increase in the share of renewable energy sources (wind, solar, etc.), variable electricity consumption schedules and changes in electricity prices in the market necessitate the use of thermal power plants in load control mode. Using the method of calculating equivalent operating hours to account for the reduction of the service life of the main equipment, the efficiency of thermal power plants in variable modes was studied. The equivalent operating hours of the K-300-240 turbine and the prime cost of electricity of the steam turbine power unit were calculated when operating in the nominal and sliding steam pressure mode depending on the level of unloading and the rate of change of output power.

1. Introduction
One of the important tasks of the development and functioning of generating capacities is the reliable regulation of the variable part of the schedule of the electrical load of energy systems and the effective provision of energy needs [1–3]. The consumption of electrical energy and power in the Unified Power System (UPS) of Russia and their forecasts are shown in figure 1 [4, 5]. According to [5] in 2025 the maximum power consumption in the UPS of Russia is projected at 169 GW, the demand for electricity by the end of the forecast period is estimated at 1,143 billion kWh per year.

The structure of the installed capacity of power plants in power systems and UPS of Russia as of 01.01.2020 is shown in table 1. When implementing the development program of the Unified Energy System of Russia for 2019 – 2025 [5], the installed capacity of power plants in UPS of Russia will increase from the actual value of 246,342.5 MW in 2019 by 1,403.1 MW and will amount to 247,745.6 MW in 2025. In the structure of installed capacity, the share of nuclear power plants (NPPs) will decrease from the actual 12.3% in 2019 to 11.8% in 2025, the share of thermal power plants (TPPs) will decrease from 66.8% to 65.7%, the share of hydroelectric power plants (HPPs) (including pumped-storage hydroelectric power plants (PSPP) and small hydroelectric plants) will increase from 20.2% in 2019 to 20.3% in 2025, the share of wind power plants (WPPs) and solar power plants (SPPs) will increase from 0.63% to 2.2% [5]. The forecast of the structure of installed capacity by type of power plants of the UPS of Russia in the period 2018-2025 is shown in figure 2.

The annual maximum power consumption of the UPS of Russia in 2019 is 151,661 MW. It was registered at 10: 00 (UTC+3: 00) on 24.01.2019 at an electric current frequency of 49.99 Hz and a load of 153,508 MW at the power plants of the UPS of Russia [4]. The structure of electricity production by type of power plants in the European part of Russia on January 21 – 27, 2019 is shown in figure 3.
Figure 1. The consumption of electrical energy and power in the Unified Power System of Russia from 1991 – 2019 and forecast until 2025 [4, 5].

Table 1. Structure of the installed capacities of the power systems of Russia as of January 1, 2020 [4].

| Power system | Total, MBr | TPPs | HPPs | NPPs | WPPs | SPPs |
|--------------|------------|------|------|------|------|------|
|              | MW        | %    | MW   | %    | MW   | %    |
| Center       | 52648.58  | 36070.23 | 68.51 | 1800.07 | 3.42 | 14778.28 | 28.07 | – | – | – |
| Middle Volga | 27493.88  | 16203.48 | 58.93 | 7013.00 | 25.51 | 4072.00 | 14.81 | 85.40 | 0.31 | 120.00 | 0.44 |
| Ural         | 53696.44  | 49979.59 | 93.08 | 1901.19 | 3.54 | 1485.00 | 2.77 | 1.66 | 0.00 | 329.00 | 0.61 |
| Northwest    | 24472.11  | 15572.14 | 63.64 | 2947.24 | 12.04 | 5947.63 | 24.30 | 5.10 | 0.02 | – | – |
| South        | 24857.73  | 13757.29 | 55.35 | 6289.69 | 25.30 | 4030.27 | 16.21 | 91.96 | 0.37 | 688.52 | 2.77 |
| Siberia      | 52104.76  | 26577.96 | 51.01 | 25301.60 | 48.56 | – | – | – | – | 225.20 | 0.43 |
| East         | 11068.95  | 6451.45 | 58.28 | 4617.50 | 41.72 | – | – | – | – | – | – |
| UPS of Russia| 246342.45 | 164612.14 | 66.82 | 49870.29 | 20.24 | 30313.18 | 12.31 | 184.12 | 0.08 | 1362.72 | 0.55 |

Figure 2. Forecast of installed capacities of UPS of Russia [5].
Figure 3. Electricity production in the European part of Russia January 21–27, 2019 (IPP – industrial power plant; CHPP – combined heat and power plant; SDPP – state district power plant).

Although the average share of electricity production by nuclear power plants in the energy balance of Russia in 2019 was 19.1%, in some energy systems of the country this share is much higher (in the Integrated Energy System of the Center – 40.8%, North-West – 34.2%, Middle Volga – 27.4%). In the Unified Power System of Russia, electricity generation by wind and solar power plants in 2019 amounted to 320.8 million kWh (0.03%) and 1284.9 million kWh (0.13%), respectively. Currently, there is a significant increase in energy production from renewable energy sources; the increase in the production of electric energy by wind farms and solar power plants in 2019 compared to 2018 was 47.3% and 69.4%, respectively [4]. In addition, the price of electricity on the market changes significantly during the day and accordingly affects the optimal load of power plants in the power system. Thus, a significant share of nuclear generation in total electricity production, an increase in the share of renewable energy sources (wind, solar, etc.), variable electricity consumption schedules and changes in electricity prices in the market necessitate the use of thermal power plants in load control mode by reducing the output power or shutdown of power units at night.

2. Theoretical positions

The operation of thermal power plants in variable mode leads to reduced efficiency, accelerated wear of equipment, increased equipment failure, increased duration of overhaul and maintenance, increased repair costs, and reduced equipment life [6–8]. All this increases the prime cost of electricity and affects the comparative efficiency of power plants in the variable part of the schedule of the electrical load [9]. Evaluation of the reduction in the cost-effectiveness and reliability of thermal power plants in variable modes is important for forecasting and forming the structure of generating capacities of power systems, evaluating the efficiency of construction of peak and half-peak power plants, choosing the optimal composition of operating equipment, and optimal parameters and operating modes of the power plant in variable mode [10, 11].

The operation of the thermal power plant in variable mode is accompanied by a deviation of the parameters of the working medium from the nominal values. Power unit capacity is regulated by changing the steam flow rate supplied to the turbine at constant parameters (at constant pressure) or by changing the flow rate and parameters of steam by regulating the pressure in the boiler and of furnace mode (at sliding pressure) [12–16]. Currently, as a rule, power units operate in the "modified sliding
pressure” mode and load regulation is carried out by simultaneously changing the steam flow rate by the turbine control valves and the flow rates of fuel, water and air into the boiler.

With rapid changes in the operating mode, the temperature quickly changes in the turbine flow part. Changes in the steam temperature lead to unsteady temperature fields in the turbine parts, which result in thermal deformations and temperature stresses. The repetition of high-temperature stresses during start-ups, shutdowns and rapid changes of capacity lead to the appearance of low-cycle fatigue cracks in the turbine parts. The most typical locations of the thermal fatigue crack formation in rotors are the thermal (compensation) grooves and disk-to-shaft fillets in the high- and low-pressure cylinders first stages, and first sections of intermediate and end seals [17–19].

The evaluation of the residual life of the steam turbine rotor was considered in studies [20–24]. In the article, the effect of operating modes on reducing the service life of the turbine rotor was taken into account using equivalent operating hours (EOHs). To calculate the EOHs, the coefficients for each mode and load change are determined [25, 26].

The economic efficiency of a thermal power plant in variable modes was determined based on calculating the cost of electricity. The cost of electricity is calculated according to the formulas presented in [27, 28] and includes: fuel costs; overhaul and repair costs; depreciation deductions; salary costs; other costs. The initial data for evaluating the efficiency of a 300 MW power unit with a K-300-240 turbine (steam parameters: pressure 23.5 MPa, temperature 560°C) in variable modes were capital investments, fuel consumption at variable loads, equipment service life, fuel cost, etc. [27, 29]. The efficiency of powerful power units is reduced during deep equipment unloading. For a 300 MW power unit, reducing the load from the nominal to 150 MW leads to an increase in specific fuel consumption by 11–12% [12]. The dependence of the specific consumption of conventional fuel for electricity of a 300 MW power unit with a K-300-240 HTGZ turbine on the capacity is shown in figure 4.

![Figure 4](image_url)

**Figure 4.** The specific consumption of conventional fuel for electricity of the power unit 300 MW depending on capacity with various control methods: 1 – at a constant initial steam pressure; 2 – at a sliding steam pressure [18, 30].

### 3. Results
Table 2 and figure 5 show the results of calculations of equivalent operating hours of the K-300-240 turbine rotor for the power change cycle (unloading from 100% to \(P\), then loading to 100%) for different power change ranges. Figure 5 shows that the service life of the turbine rotor in a variable mode of operation at constant initial pressure is significantly reduced only with deep unloading and a high rate of power change. The reduction in the service life of the turbine rotor due to low-cycle fatigue depends on the temperature stresses in the metal, determined by the range and rate of change of the steam temperature in the flow part of the turbine, which in turn depends on the range and rate of change of
capacity of the power unit. Therefore, by setting a load change schedule, it is possible to control a decrease in the service life of the rotor. When operating in the sliding pressure mode, the steam temperature changes slightly, therefore, the rate of change of the load (within the control range) in this operating mode may be greater. One cycle of 100–50–100% power change at a speed of 3 MW / min (1%/min) in this mode (figure 5) results in a slight reduction in the service life of the turbine rotor – 0.08 equivalent hours.

**Table 2.** Results of calculations of reducing the life of the K-300-240 turbine rotor when operating in variable mode.

| Turbine power at unloading $P$ (MW) | Power variation time, min$^a$ | Strain range during a cycle, $\Delta\varepsilon \times 10^3$ | Number of cycles to failure $[N]$ | Equivalent operating hours |
|-----------------------------------|-------------------------------|---------------------------------|---------------------------------|--------------------------|
| at sliding pressure and power change rate of 3 MW / min | | | | |
| 270 | 90 | 10 | 0.0077 | 2845821 | 0.070 |
| 240 | 80 | 20 | 0.0000 | 2703095 | 0.074 |
| 210 | 70 | 30 | 0.0108 | 261166 | 0.077 |
| 180 | 60 | 40 | 0.0000 | 2554619 | 0.078 |
| 150 | 50 | 50 | 0.0134 | 2520691 | 0.079 |
| at constant pressure and rate of change of power 2 MW / min | | | | |
| 270 | 90 | 15 | 0.211 | 321769 | 0.62 |
| 240 | 80 | 30 | 0.315 | 71332 | 2.80 |
| 210 | 70 | 45 | 0.351 | 38312 | 5.22 |
| 180 | 60 | 60 | 0.355 | 35956 | 5.56 |
| 150 | 50 | 75 | 0.358 | 34076 | 5.87 |

$^a$ the same when loading and unloading

**Figure 5.** Equivalent operating hours of the K-300-240 turbine rotor per cycle of power change (unloading from 100% to $P$, then loading to 100%) for different power change ranges:

1 – at a sliding pressure of 3 MW/min; 2, 3, 4, 5, 6 – at constant pressure, respectively 2; 2.25; 2.5; 2.75; 3 MW/min.

Figure 6 shows the change in the prime cost of electricity (average for the calculated period of 30 years) of a power unit with a K-300-240 turbine when operating 16 hours at 100% capacity and
Unloading for 8 hours at night to capacity $P$. The minimum increase in the power plant's cost of electricity when operating in variable mode will be when operating at a sliding pressure – when unloading for 8 hours a day by 50%, the prime cost of electricity increases compared to the base-load mode by 1.07 US cent/kWh (11%). The dash-dotted line in figure 6 shows the prime cost of electricity at a power plant when operating at a constant output power level $P$ during the day. Figure 6 shows that at a high rate of power change when operating at constant pressure (2.5 MW/min – line 4) when unloading the power unit (with 100% day) below 72.5% for 8 hours at night, the average prime cost of electricity for 24 hours will be higher than the prime cost of the power unit operating at a constant (reduced) power level $P$ (gray area). In this case, more electricity is generated (and therefore more revenue from its sale) compared to operating at a constant reduced power level, but the prime cost of electricity is higher due to the reduction of the life of the turbine rotor (and other important components) and additional repair costs.

![Figure 6](image-url)

**Figure 6.** The cost of electricity for the power unit 300 MW during daily unloading with different control methods (1–4, similar to figure 5) – the prime cost of electricity when operating at a constant power level $P$.

### 4. Conclusions

Using the method of calculating equivalent operating hours to account for the reduction of the service life of the main equipment, the efficiency of thermal power plants in variable modes was studied. The proposed procedure allows you to evaluate the additional costs associated with flexible operation and choose the optimal mode of operation of the power plant. An example of calculating the equivalent operation hours of the K-300-240 turbine and the prime cost of electricity of the steam turbine power unit when operating in nominal and sliding steam pressure depending on the level of unloading and the rate of change of output power. The operation of a 300 MW steam turbine power unit in variable mode is most effective on a sliding steam pressure – when unloading up to 50% of the power for 8 hours at night, the average cost of electricity increases by 1.07 cents/kWh (11%) compared to the base-load mode.

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