Research Paper Engineering

# Effectiveness of models usage for CCPP-450 start-ups analysis


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**ABSTRACT**

Technology research of variable modes traditionally is held experimentally. In modern market conditions the possibility of scale long time industrial experiments decreased significantly. In this connection mathematical models of power plants allow to reduce number of experiments on real equipment.

It is proposed to carry out start-up tests using the combined-cycle power plant (CCPP) dynamic mathematical models. Tests were conducted for hot start-ups as the most common of the starting modes entire spectrum. They were implemented in full accordance with the actual operating conditions after CCPP 6-8 - hour outage.

The results of this mathematical test were taken as an input data for the critical elements thermal-stress state and damage analysis based on the equivalent operating hours criteria.

As a result of these tests the 30-40 minutes duration hot CCPP-450 start-up assignment schedule was worked out. This start-up assignment schedule ensured compliance with basic equipment reliability criteria. This ability was confirmed by CCPP-450 hot start-up which was carried out at one of the Moscow power stations.



| **KEYWORDS** | Combined-cycle power plant, Gas turbine unit, Steam turbine, Mathematical model, Mathematical simulation, Hot start-up |
|---|---|


## Introduction

Traditionally technology research of variable modes is held experimentally, when detailed test program is developed in the form of an algorithm, continuously performing technological operations with showing all the restrictions, arising during the CCPP start-up, and then industrial experiments are carried out.

In modern conditions, which are characterized by market relationships between energy generating companies and the system operator, the possibility to conduct large-scale and long-duration industrial experiments decreased significantly [1]. In this regard, the opportunity of virtual testing on dynamic mathematical models of power generating units can significantly reduce the number of experiments on real equipment. This approach has become particularly relevant for combined cycle power plants (CCPP) with heat recovery steam generators (HRSG), the amount of which has a constant tendency to increase in Russia power engineering, and characterized by high efficiency, cyclic load capability and automation level.

Modern full-scale mathematical dynamic models of power plant units give an opportunity to start up units in full accordance with the actual operating conditions.

Using small sampling spacing, makes it possible to adequately reflect transients in control circuits such as gas and steam turbines' velocity regulators, HSRG feed controller, etc.

Mathematical model specifications fully comply with the characteristics of real power plants, including fully reproduced automatic control system and automatic control of main and auxiliary power plant equipment.

The mathematical model of combined cycle power plant CCPP-450 hot start-up tests will be described below.

## Tests of CCPP-450 Hot Start-ups Mathematical Model

Due to the fact that hot start-up has benefits in fuel consumption during the CCPP operation in the variable part of the load schedules because of its minimum duration, this type of start-up has been adopted as a basis for carrying out the mathematical experiment (Fig. 1). The CCPP-450 starting technology was adopted with two gas turbines and heat recovery steam generators parallel loading to 90 MW (that was an output of each of them) and their following loading up to the rated power together with steam turbine. The gas turbine unit (GTU) output was chosen in such a manner that after the steam turbine start-up its control valves were opened almost completely. This made it possible to carry out the subsequent loading of the power plant unit only by GTU parallel loading. At that time the steam turbine was working at a sliding pressure of high pressure steam circuit and was increasing its capacity by changing evaporation rate of the heat recovery steam generators.

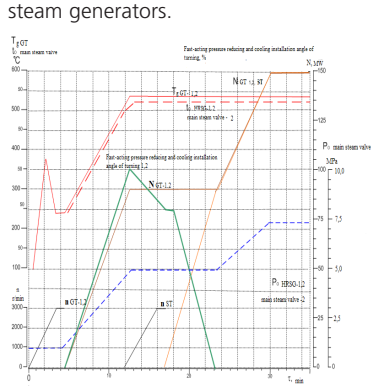


**Figure 1. CCPP-450 hot start-up schedule assignment with two GT-1, 2 parallel start-up**

(HP cylinder temperature >290°C)

In accordance with the real object technology after getting permission to start-up GTU the automatic GTU-1 and GTU-2 start-up programs begin to work. Both GTU rotors are accelerated to 600 rev / min to perform pre-start 10 minutes ventilation of HRSG flue.

At the end of ventilation after the fuel ignition in the combustion chambers of both gas turbines they are run up to idle and generators synchronization. Then both GTU with their heat recovery steam generators are being loaded to 90 MW with 11 MW/min rate of loading.

Upon reaching the 90MW capacity of each of the started-up GTU steam is supplied to a steam turbine and after the synchronization parallel loading of all the generators with fully open steam turbine valves is carried out.

Using small sampling spacing (~100 ms) makes it possible to adequately reflect transients in control circuits such as gas and steam turbines' velocity regulators, heat-recovery steam generator feed controller, etc.

Mathematical model specifications fully comply with the characteristics of real power plants, including fully reproduced automatic control system and automatic control of main and auxiliary power plant equipment.

**The mathematical model of combined cycle power plant CCPP-450T hot start-up tests will be described below.**
Thermal Stress Analysis of the Critical Elements of the CCPP-450 Steam Part during Hot Start-ups

It is known that maximum thermal stresses occur with increasing temperature in such elements of the cycle steam part as high (intermediate) pressure drums, high (intermediate) pressure outlet steam headers of HRSG and steam-lines;` the most loaded elements of steam turbines are HP (IP) stop valves' casings and HP (IP) rotors. In solving the problem of heat conduction on the inner surface thermal stress-state calculations were carried out using the convective heat exchange equation, which is determined by film coefficient $\alpha(\tau)$ and environment temperature $t_c(\tau)$, that for each point of the inner surface can be written as [2]:

$$-\lambda_s(\partial t/\partial n)=\alpha(\tau)[t_c(\tau)-t_s(\tau)],$$

where $t_s$ - steam temperature, ◦C;

$\lambda_s$ – thermal conductivity, W/(m ◦C).

The strength-strain state estimate was carried out using the equivalent stresses defined as the algebraic difference of the main normal stresses $\sigma_1$, $\sigma_2$, $\sigma_3$, which were obtained as a result of the critical element thermal strength-strain state calculations. Construction durability under the combined action of fatigue and creep at temperatures above 450°C was evaluated in accordance with the relationship:

$$\sum N_i/[N]_i+(1,25\sigma_c/\sigma_{t/}\tau)^m\le D_c,$$

where $N_i$ is the number of the *i*th-type loading cycles;

$[N^*]_i$ is the permissible number of the *i*th- type loading cycles;

$\sigma_c$ is the design creep stress, which is the local maximum of the main normal stress calculated, taking into account plasticity and creep at nominal operating conditions;

$\sigma_{t/}\tau$ is the conventional long-term tensile strength, MPa;

m is the exponent in the long-term strength equation;

$D_c$ is the parameter characterizing the permissible damage under the combined effect of fatigue and creep.

**The permissible number of cycles [N*] determined from the formula**

$$[N^*]=[N]/[D_c-(1,25\sigma_c/\sigma_{t/}\tau)^m=[N]/\Pi_N$$

$$\Pi_N=1/[D_c-(1,25\sigma_c/\sigma_{t/}\tau)^m]$$

If creep is not taken into account $\Pi_N=1$. The results of HP outlet superheater header calculation are represented in Table 1 and in Fig.2.

The conditions, determining the thermal strength of the HP drums' metal are the difference between the temperatures of the upper and lower drum's generating lines, the temperature difference across the wall thickness and the internal pressure (vapor pressure in the drum casing).

During model hot start-up thermal stresses maximum was 59 MPa at pressure rising rate about 0.33 MPa / min, the rising rate of the high pressure drum's casing temperature was 6°C per minute, and the maximum temperature difference between the top and the bottom of the high pressure drum - 23 degrees.

**Table 1. Results of HP outlet header stress calculation**

| №№ | σ13,max=(σ1-σ3) max, [MPa] | Stress amplitude σa, [MPa] | [N*] |
|---|---|---|---|
| 1 | | | |
| 2 | 115,9 | 58 | >260000 |
| 3 | | | |

**Table 1. Continuation**

| №№ | Metal temperature [°C] | Steam temperature [°C] | Power, [MW] | Heating rate, [°C/min] |
|---|---|---|---|---|
| 1 | 220,2 | 212,8 | 3 | |
| 2 | 220,5 | 215 | 19,8 | 22,4 |
| 3 | 379,7 | 459 | 90,3 | |

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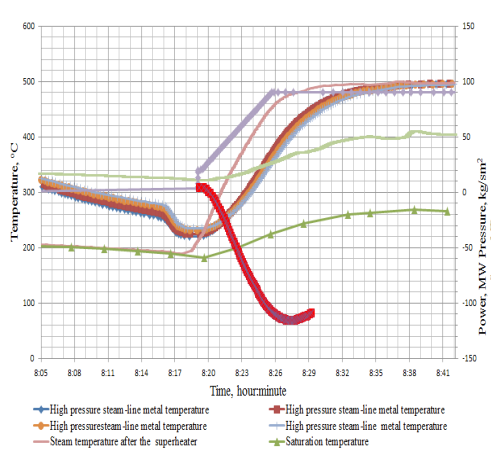



**Figure 2. HRSG steam-line high pressure steam parame-**

**ters. Time 8:05-8:41**

During model hot start-up the thermal stresses maximum was 59 MPa at pressure rising rate about 0.33 MPa / min, the rising rate of the HP drum casing temperature was 6°C per minute, and the maximum temperature difference between the top and the bottom of the high pressure drum - 23 degrees.

Thus, the fatigue strength of high and low pressure drums is provided with a significant margin.

The temperature state of the HP stop valves casings was such that the temperature difference through the wall thickness did not exceed 20°C at an initial temperature of the HP stop valve casing 20°C.

Table 2 shows the calculated values of stresses in the steam turbine rotor appearing at the turbine start-ups from different initial temperature states, stationary operation, as well as from the centrifugal forces in the most loaded section of the intermediate seal.

**Table 2. Results of HP outlet header stress calculation**

| Zone | Stresses on the intermediate seal surface [MPa] | |
|---|---|---|
| Operating regime | Centrifugal forces | Stationary operation |
| Temperature, [°C] | - | 507 |
| $\sigma_r$ | 0 | 0 |
| σθ | 8,8 | -2,3 |
| $\sigma_z$ | -7 | 6,6 |
| $\tau_{rz}$ | 0 | 0 |
| $\sigma_i$ | 13,8 | 8,0 |

**Table 2. Continuation**

| Zone | Stresses on the intermediate seal surface [MPa] | | | |
|---|---|---|---|---|
| Operating regime | Hot start-up | Warm start-up | Cold start-up | Shut-down |
| Temperature, [°C] | 501 | 482 | 260 | 499 |
| σr | 1,33 | -16,3 | 0 | 0 |
| σθ | -150,2 | -187 | -268,5 | 8,0 |
| σz | -40 | -3,6 | -166 | 25,7 |
| τrz | 0 | 0 | 0 | 0 |
| σi | 138 | 178 | 236 | 22,8 |

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| σz | -7 | 6,6 | -40 | -3,6 | -166 | 25,7 |
| τrz | 0 | 0 | 0 | 0 | 0 | 0 |
| σi | 13,8 | 8,0 | 138 | 178 | 236 | 22,8 |

Based on the computational research it can be said that there are no low-cycle thermal fatigue limitation in all critical areas of the HP rotor during hot and warm start-ups.

As can be seen from the above data, the greatest of considered stresses occur at the final heating stage in HP outlet superheater headers. In this case equivalent stress amplitude is 58 MPa at maximum cycle temperature of 500°C. According to the low-cycle fatigue curves such a stresses amplitude and maximum cycle temperature of 500°C, corresponds to the permissible number of cycles, significantly greater than [N]=2·10$^5$. Generally HP superheater outlet header lifetime resource is 200,000 hours. Thus, each start-up with the steam temperature increasing rate equal to 22 and equivalent stress amplitude of 60 MPa leads to an expenditure of no more than 1 equivalent operating hour.

The dependence of the equivalent operating hours on the initial metal temperature for the HP superheater outlet header, as the most-stressed (critical) CCPP element, is presented in Fig.3.

Number of GTU equivalent operating hours at such start-ups will be equal to about 10 hours.

Number of equivalent operating hours of the steam part of the steam-gas cycle does not have any noticeable effect on the resource consumption of highly stressed parts of CCPP.

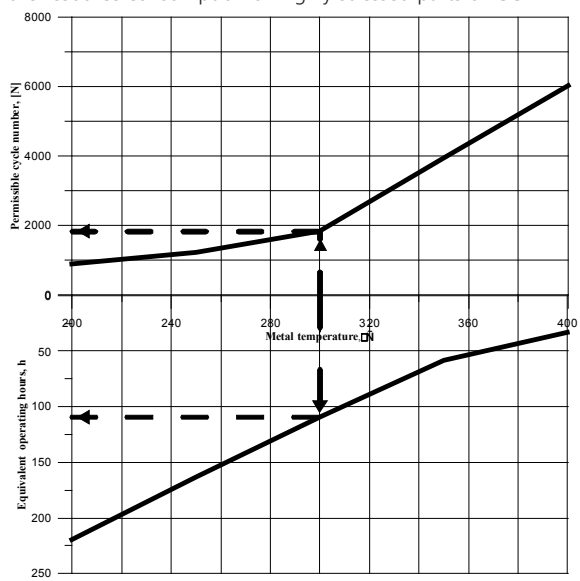



**Figure 3. The dependence of the equivalent operating hours on the initial metal temperature for the HP superheater outlet header**

**CCPP-450 hot start-up at the cogeneration plant number 27**

To confirm the results of the calculations an experimental hot start-up of one of the gas turbines with the HRSG was conducted. It took place at the real cogeneration power plant number 27 Mosenergo (unit number 3) CCPP-450.

For this purpose HP and LP steam from the HRSG of one of the two power plant gas-turbine units was transferred to a steam turbine condenser. Then, this GTU was unloaded to 4.5 MW power at a rate of 11 MW / min. At the achieved power level 15 minutes delay was made to reduce the temperature of the heat recovery steam generator components to the desired values. When delay was finished GTU with heat recovery steam generator was loaded to its nominal rating power (about 150MW) at a rate of 11 MW/min.

The experiment that has been carried out corresponds to power plant unit hot start-up after about 8 hours outage in reserve (Fig.3).



**Figure 4. CCPP-450 power plant unit start-up without**

**steam turbine.**
1 - GTU output; 2 - HP steam temperature after HRSG; 3 - Fast-acting pressure reducing and cooling installation angle of turning; 4 - Metal temperature of the upper point of HP drum; 5 - Metal temperature of the bottom point of HP drum; 6 – HP drum level; 7 – HP drum pressure; 8 – Outlet HP superheater steam pressure; 9 – HP steam-line temperature

Start-up schedule with each gas turbine loading rate obtained during the experimental start-up (Fig. 4) and the same initial temperature of the steam part of the equipment, demonstrates the ability of CCPP-450 hot start-up for 35-40 minutes

**Summary**
1. CCPP-450 hot start-ups were held on the installation mathematical model, made with the full composition of APCS automatic regulators, installed at the operating power plant.
2. Number of equivalent operating hours of the cycle steam part has no effect on the CCPP life utilization at such start-ups.
3. The 30-40 minutes duration hot start-up schedule for CCPP was proposed, developed to compliance with the basic criteria of reliability. It is shown that the duration of the CCPP-450 hot start-up with holding at an intermediate power about 90 MW and with continuous power plant loading without any delay don't differ in time but in terms of start-up automation the delay is more preferable.
4. Tests carried on the real power plant unit confirmed the results obtained on the model.

## REFERENCES

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