Applying the equivalent operating hours principle for assignment of CCPP equipment maintenance period

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Abstract. CCPP cyclic load changes required the thermal stress and cyclic strength operational control of the steam path "critical" elements. Accumulated damage and residual life assessment are necessary for timely equipment maintenance. The basis of maintenance activities planning is the accounting of the resource consumed by "critical" equipment elements during operation. The creation of on-line mathematical models of steam path "critical" elements is carried out on the way of their sequential simplification with the aim of obtaining simple for implementation models adequately reflecting the physical processes occurring in them. The program of operational control of equivalent operating hours accumulated by CCPP steam path "critical" elements allows to estimate their thermal stress state and cyclic strength by processing operational measurements. Collection and processing data on CCPP equipment failures from the point of view equivalent operating hours accumulated by the time of failure give an ability to form schedules of preventive measures that is inspections.

The raised damaging of the CCPP cycle steam part equipment is associated with cyclic changes of load and required a change in the philosophy of CCPP variable modes, which cause necessity an on-line control of the thermo-stressed state and fatigue strength of the "critical" elements of the steam path, accumulated damaging and residual life for timely in carrying out maintenance.

Accounting of the resource share that was expended by "critical" elements of the equipment during operation is the heart of the maintenance planning system used by foreign companies. Some firms, for example, GE Energy, take into account the maximum permissible operating time and the number of startups, while others, such as Siemens, build their maintenance system based on accounting of the equivalent operating hours accumulated during operation. In the Russian Federation, the concept of equivalent operating hours for determining the frequency of maintenance and repair is applied only for gas turbine plants [2]. Equivalent operating hours $T_{eqv}$, calculated using the formula (1), can determine the interval duration between revisions.

$$T_{eqv} = \sum_{i=1}^{n_i} a_i n_i + \sum_{j=1}^{\tau_j} b_j \tau_j$$  

(1)

where $n_i$ – the number of i-type startups;
$\tau_j$ – the operating time at the sudden temperature changes, for example due to a step changes of load within adjustment range limits or shutdowns;
$b_1 = 1$ – base load coefficient;
$\tau_1$ – base load operation hours.

The basis of the choice of coefficients, characterizing the different operating regime impact on the equipment life is the damageability summation equation, written in the following form:
where $[N]_i$ – permissible number of loading cycles, determined at the stress level $(\sigma_a)_i$ of the i-th mode;

$\tau_j$ – stationary operation time for the estimated service life at the j-th rated load under its stepwise change conditions;

$\tau_j^*$ – the time to failure, determined by the long-time strength equation at the j-th rated load under its stepwise change conditions;

As a coefficient for each start is considered the relationship:

$$a_i = \frac{\tau}{d_{sum}} \cdot \frac{1}{[N]_i^*}$$

where $T$ – the equipment resource, given by the manufacturing specifications, h;

$$b_j = \frac{\tau}{d_{sum}} \cdot \frac{1}{\tau_j^*}$$

where $d_{sum}$ – accumulated damage.

The approach, based on the evaluation of accumulated equivalent operating hours, makes it possible to create a unified system involving all the critical elements of the CCPP thermal scheme.

As an example, the so-called "resource counter" of the high-pressure steam superheater header, which is a "critical element" at the start-up initial stages. It is heated at minimal steam flow from the HRSG and its high temperature, practically not different from the temperature of the gas turbine gases at HRSG inlet.

In the analysis of its operating conditions, it is also necessary to take into account thermal and hydraulic maldistribution in the superheater piping systems which is observed at this startup stage. The need for forced cooldown of the gas turbine unit for several hours after its shutdown and mandatory 5-10 minutes ventilation of the heat recovery steam generator gas path before the unit starting lead to intensive cooling of the HP superheater outlet header metal, especially during winter shutdowns [3]. Therefore, most of the startups can be considered as cold start-ups for the high-pressure superheater outlet headers, the number of which, under the current requirements can reach 2000 for cycling combined-cycle power plants.

When developing the “resource counter” program, simple algorithms based on simple in terms of implementation mathematical models should be used, reliable, having sufficient accuracy and at the same time adequately describing the operation of the corresponding steam path elements.

Numerous researches preceded the creation of outlet superheater header model. They were carried out on header models with a number of branch pipes (figure 1a), which took into account thermal and hydraulic maldistribution, three-dimensional models with one branch pipe (figure 1b), three-dimensional models in which the influence of the pipes was taken into account using stress concentration factors and axisymmetric models.

As a result of these researches, conclusions were made about the unloading action of neighboring nozzles in models with a number of pipes, which allowed limiting to one branch pipe. The values of concentration factors of circumferential and axial stresses were obtained as a function of the ratio of the branch pipe and the header internal diameters, as well as the B, [4] criterion. These values are less than the value recommended by normative documents [5], which is equal to 2 (table 1).

As a result one-dimensional model of temperature and stress calculations, taking into account the effect of the branch pipes with the help of stress concentration factors for the outlet superheater header was used in the automatic program “resource on-line counter”.

The boundary conditions were determined on the basis of the measured operating parameters for convective heat transfer.

At the end of the cycle "startup – stationary mode – shutdown", the number of equivalent operating hours accumulated per cycle was calculated. Their total quantity, stored in the database, serves as the basis for the carrying out maintenance activities.

As an example, table 2 shows the values of equivalent operating hours accumulated by steam and gas turbines, as well as by the high pressure outlet superheater header Ø406.4x51 mm CCPP-450 unit No. 1 of North-West CHP.
Figure 1. Calculation of the header thermal stress state using finite element model:
a) – three-dimensional model of the header with 12 branch pipes and the results of stress intensity calculation; b) – three-dimensional model of a header with one branch pipe and the results of stress intensity calculation; c) – three-dimensional model of the header, taking into account the influence of the pipe by using the stress concentration factor, and the results of the stress intensity calculation.

Table 1. Temperature stresses concentration factor.

| Dimension-type | Temperature stress concentration factor value |
|----------------|-----------------------------------------------|
| Header | Nozzle | Standard 55682.3-2013 Euro Norm EN 12952-3 | TRD 301 | GD 10-249-98 [5] | Calculation data VTI [4] |
| 465x22 | 38x3 | 1.736 | 2 | 2 | 1.405 |
| 426x34 | 38x3 | 1.707 | 2 | 2 | 1.425 |
| 325x25 | 108x12.5 | 1.266 | 2 | 2 | 1.205 |
| 273x20 | 38x3 | 1.586 | 2 | 2 | 1.450 |
| 406.4x51 | 38x3 | 1.683 | 2 | 2 | 1.435 |
| 273x30 | 28x4 | 1.682 | 2 | 2 | 1.530 |
| 426x36 | 38x3.5 | 1.710 | 2 | 2 | 1.425 |
| 219x20 | 108x10 | 1.063 | 2 | 2 | 1.100 |

Table 2.

Steam turbine ST-10

| Date | Total time operating age | Time since overhaul | Number of load startups | Total startups since new | Including cold startups | For operation under creep in static load | For startups | Summary |
|------|--------------------------|---------------------|------------------------|--------------------------|-------------------------|-----------------------------------------|--------------|---------|
| 01.05.2001 | 558.833 | | | | 18 | 15 | 25.0 | 393.1 | 418.0 |
| 01.02.2002 | 6055.5 | | | | 38 | 32 | 42.0 | 838.2 | 881.0 |
| 01.01.2009 | 5950.13 | | | | 97 | 82 | 2582.8 | 2147.4 | 4730.2 |
| 15.09.2009 | 65008 | 6055.5 | | | 100 | 85 | 2822.6 | 2225.4 | 5048.0 |
| 01.02.2012 | 82229.9 | 9376.1 | | | 117 | 99 | 3570.4 | 2592.5 | 6162.9 |
| 01.08.2017 | 121508.7 | 15446.2 the overhaul 2015 | | | 162 | 137 | 5275.8 | 3587.6 | 8863.4 |

GTU-11

| Date | Total time operating age | Time since overhaul | Number of load startups | The number of accumulated equivalent operating hours since new | Since an overhaul | Under load operating age | Number of load startups since new | The number of accumulated equivalent operating hours since new | Since an overhaul |
|------|--------------------------|---------------------|------------------------|-----------------------------------------------|----------------|------------------------|--------------|-----------------------------------------------|----------------|
| 01.05.2001 | 666.2 | | 18 | 2258 | 255.2 | 15 | 592 |
| 01.02.2002 | 4932.8 | | 78 | 7843.9 | 4835.2 | 54 | 5066.5 |
| 01.01.2009 | | | | | | | | | |
| 15.09.2009 | 75419.6 | 8173.7 | 200 | 121153.5 | 15877.2 | 103477.5 | 67729.4 | 6431.2 | 8356.4 the overhaul 2016 | 263 | 112259.1 | 8934.1 |
| 01.08.2017 | 111825.3 | 14907.5 | 314 | 121153.5 | 15877.2 | 103477.5 | 67729.4 | 6431.2 | 8356.4 the overhaul 2015 | 263 | 112259.1 | 8934.1 |

GTU-12
As can be seen from the table above, the equivalent operating hours can be considered as a characteristic of the equipment state, which is very important in the transition from preventive maintenance to repair according to the current state.

According to the data and normative documents regulating the timing of boilers, steam and gas turbines elements inspections, the steam turbine was overhauled, having worked under load 121509 h by 01.08.2017. At the same time the number of equivalent operating hours accumulated for the entire operation period to 01.08.2017 was 8863 hours. The number of equivalent operating hours accumulated for the same period by outlet high pressure superheater header of HRSG-11 was 14907.5 hours and of HRSG-12 – 8356.4 hours. It should also be noted that, due to the difference in the applying materials properties for steam turbines, the number of starts is important in the equivalent operating hours accumulation process, and for outlet high pressure superheater headers the maximum permissible operating time is important.

Existing maintenance activities deadlines, given by the normative documents [6, 7] (figure 2) can be converted into accumulated equivalent operating hours.

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**HRSG-11 (the high pressure outlet superheater header)**

| Date          | Under load operating age | Number of load startups | The number of accumulated equivalent operating hours |
|---------------|--------------------------|-------------------------|-----------------------------------------------------|
|               | Total time since new     | Time since overhaul     | Since new                                           | Including cold startups | For operation under creep in static load | For startups | Summary |
| 01.05.2001    | 666.3                    |                         | 18                                                  | 15                      | 145.3                                | 13.7         | 158.9   |
| 01.02.2002    | 4932.8                   |                         | 78                                                  | 66                      | 1075.6                               | 59.4         | 1135    |
| 01.01.2009    | 55230.8                  |                         | 200                                                 | 170                     | 24382.5 GTU overhaul 2015            | 152.6        | 16597.2 |
| 15.09.2009    |                         |                         | 314                                                 | 267                     | 16444.6                              | 239.6        | 34622.1 |
| 01.02.2012    | 75419.6                  | 8173.7                  | 200                                                 | 170                     | 1782.2                              |             |         |
|               |                         | 14907.5                 | 314                                                 | 267                     | 24382.5 GTU overhaul 2015            |             |         |
| 01.08.2017    | 111825.3                 | GTU overhaul 2015       | 314                                                 | 267                     | 16444.6                              |             |         |
|               |                         |                        |                                                     |                         | 1782.2                              |             |         |

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Figure 2.

1 – The period of GTU control activities is 30000 h; 2 – The period of GTU control activities is 60000 h; 3 – The period of steam turbine control activities is 25000 h; 4 – The period of steam turbine control activities is 50000 h; 5 – The period of HRSG control activities is 50000 h; 6 – The period of HRSG control activities is 100000 h.

Conclusions

The main stages of creation an automated system for determining the maintenance activities timing are:

1. Creation of the mathematical models of steam path "critical" elements is based on the results of computational and experimental studies and is carried out on the way of their sequential simplification in order to obtain simple to implement on-line models that adequately reflect the physical processes occurring in them.

2. Development of an operational control program over the equivalent operating hours accumulated by the considered CCPP steam path "critical" elements that have to meet the requirements for the automated process control system software. This program allows presiding on-line the thermal stress state and cyclic strength evaluation based on the results of operational measurements processing.

3. Collecting and processing data on failures of CCPP equipment elements in terms of the equivalent operating hours accumulated by the time of failure and the development on this basis inspections schedules. Before the statistical processing of available information is completed, the existing inspections schedules can be converted in terms of accumulated equivalent operating hours.

References

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