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Cyclic operation of large-capacity steam turbines

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Abstract

Today, cyclic operation is a typical operational mode for large-capacity steam turbines, which results from the overall situation in the electricity market. Additional life consumption due to creep-fatigue interaction, wear and tear and corrosion in specific components are principle effects of cyclic operation. So far cyclic operation has not been practised in the 500 MW units of V-EG, but preventive analyses of additional life consumption of critical components help to identify weak points and to avoid forced outages. The authors report about their life-consumption analyses of the IP rotor of a 500 MW steam turbine. The presentation addresses collection of operating data and their generalisation in pattern cycles, calculation of thermal and mechanical boundary conditions, FEM modelling of the rotor, analysis of the stresses and their ranges and finally the life assessment. Although the analysis of the specific turbine showed that no adverse effect with regard to forced life consumption is expected for cyclic operation, the authors draw precise conclusions with regard to enhanced creep monitoring.

Keywords: Steam turbine; Cyclic operation; Life assessment

1 Introduction

Power plants are designed for base, medium or peak load according to their type and capacity. Traditionally, units of high specific capital investment are only

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profitable in base load operation and others with high fuel costs in peak load operation only. But today; after deregulation of the European electricity market the utilities are faced with the challenges of fluctuating energy demand and influences of price level. In addition the German energy policy with its support of renewable energy results in alternating power generation due to meteorological conditions by wind-based power. After all, today the control area of VE-G is influenced by more than 2170 MW wind power capacity [1] and the well-known problem that their supply cannot be scheduled. In addition, no correlation exists between supply and demand. VE-G is faced with the situation that wind-based power can rise up to 50 % of the installed wind power capacity in periods with heavy blowing wind [1], which has completely to be balanced by the responsible transmission system operator. If this happens at low load, base load units will be shut down accordingly.

VE-G's supercritical lignite-fired units of the 800/900 MW class and the retrofitted 500 MW units belong to those power plants with favourable generation costs on a long-term basis. Thus, this overall situation results in two typical scenarios of plant operation: high load and cyclic operation. While high load operation has already been applied in the 500 MW units on the basis of turbine retrofits with resulting increase in unit output at the same steam generating output (Fig. 1), cyclic operation has not been practiced in the large-capacity lignite fired units of VE-G so far. But, this is a future possible operational mode of the 500 MW units.

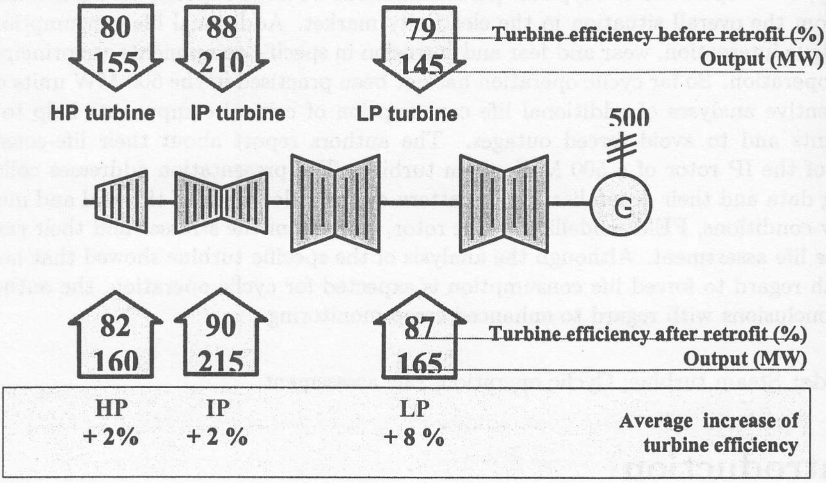

Figure 1. Retrofit of the 500MW steam turbines of the power plant Jaenschwalde.

2 Principle effects of cyclic operation on material degradation in large-capacity steam turbines

Additional life consumption due to creep-fatigue interaction, wear and tear, and corrosion in specific components are the principle effects of cyclic operation on plant components. The turbine can mainly be effected by additional fatigue, which interacts with the material degradation from creep in the HP and IP turbine rotors, the stop and control valves and the turbine casings. These regions are distinguished by thermal mechanical loading and geometrical inhomogeneities (transition curves, grooves, drill holes etc.) with resulting local stress concentrations and multiaxial stress fields. Fig. 2 shows the regions mainly affected by cycling of a 500 MW steam turbine.

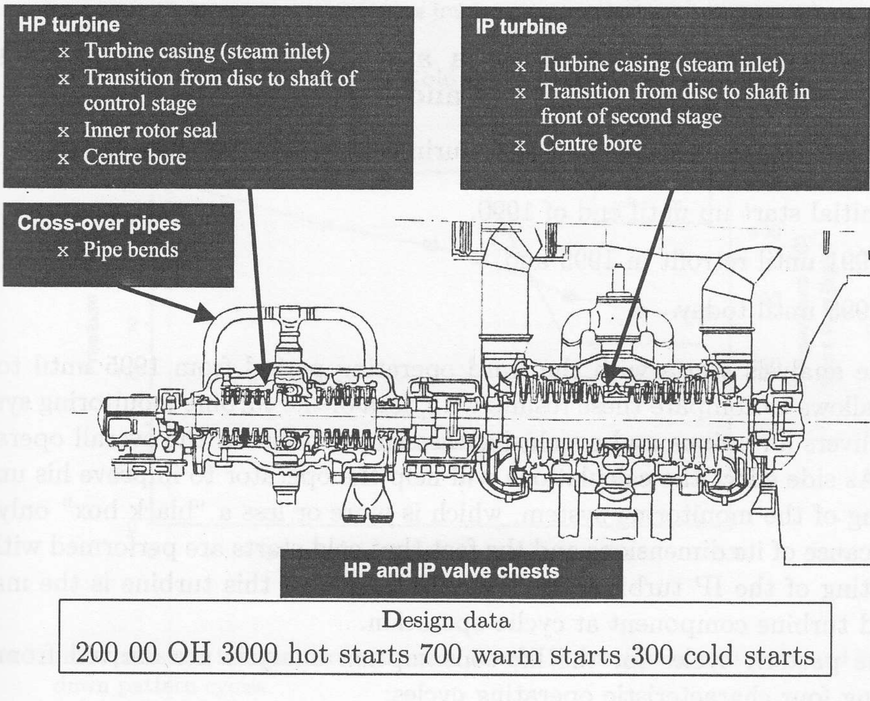

Figure 2. Critical areas of interacting creep and fatigue of a 500 MW steam turbine.

But, fatigue does not influence the turbine performance at cyclic operation only. Particular attention has also to be paid to axial and radial clearances to avoid both increasing leakage losses and damage due to clearance bridging.

3 Life-consumption analyses of the IP rotor of a 500 MW steam turbine for cyclic operation

3.1 General

Before moving to cyclic operation VE-G is careful to reduce the risk of decreasing reliability and availability already in advance without taking the risk of increase in forced outages and their costs. Thus, foresighted life-consumption analyses of the turbine were performed to identify weak points with regard to the planned operational mode. One 500 MW unit of the lignite-fired power plant Jaenschwalde was selected as reference unit. The unit was commissioned in 1983. During retrofit in 1995, the on-line turbine monitoring system was installed so that life consumption has been monitored since that time. Because the initial life consumption was set zero, the total value since commissioning is unknown. The gap has to be closed now. The approach is the following.

3.2 Analysis of operating data and deriving pattern cycles of cold, warm and hot starts and shutdowns

Three characteristic periods exist during the whole operating time:

- initial start up until end of 1990,
- 1991 until retrofit in 1995 and,
- 1995 until today.

The analysis starts with the third operating period from 1995 until today, which allows to compare these results with data of the turbine monitoring system and delivers an unique and conclusive assessment basis for the overall operating time. As side effect the calculations will help the operator to improve his understanding of the monitoring system, which is more or less a "black box" only.

Because of its dimensions and the fact that cold starts are performed without preheating of the IP turbine, the IP turbine rotor of this turbine is the mainly effected turbine component at cyclic operation.

The pattern cycles for the life-consumption analysis are derived from the following four characteristic operating cycles:

- cold start – cold shutdown (Fig. 3),
- warm start – partial cold shutdown,
- warm start – natural cooling down,
- hot start – natural cooling down.

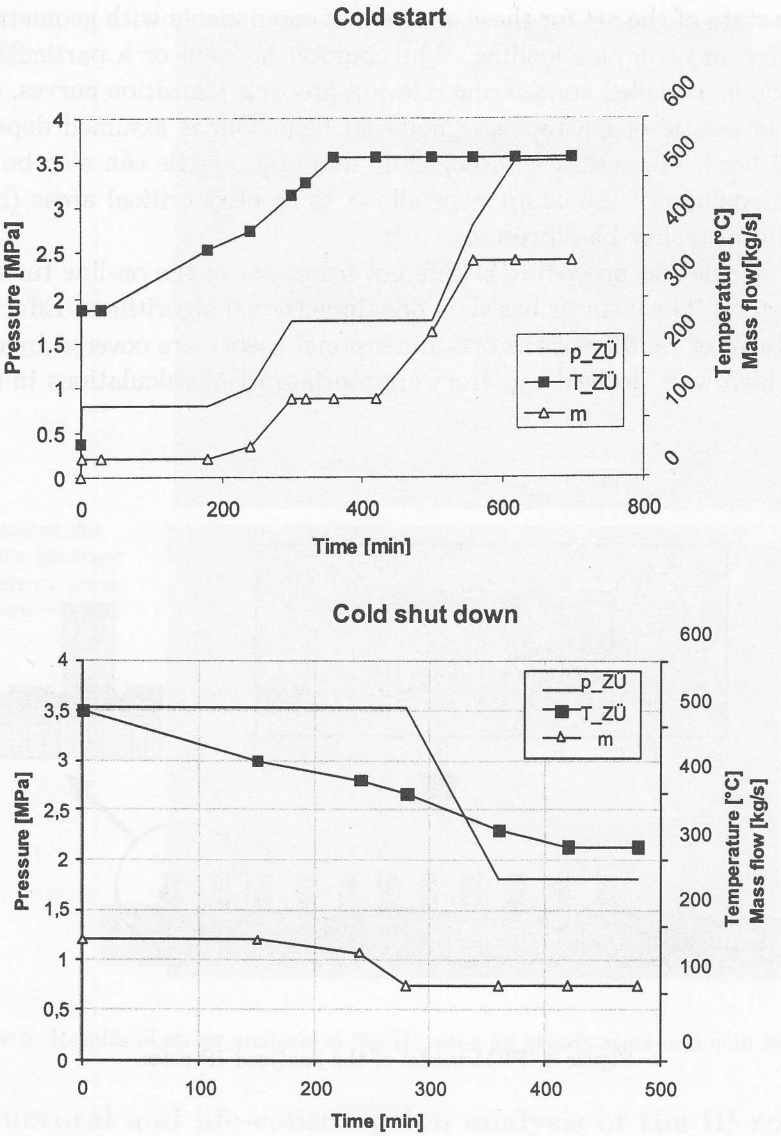

Figure 3. Inlet pressure, temperature and mass flow of IP turbine in cold start and cold shut down pattern cycles.

3.3 Thermodynamic recalculation of the IP turbine and modelling of the rotor

The thermodynamic recalculation delivers steam temperatures and pressures in the turbine stages for the pattern cycles, which are the boundary conditions for the following temperature and stress analysis. Today, the finite element method

(FEM) is state of the art for those analyses of components with geometrical inhomogeneities and complex loading. The component itself or a particular component region is modelled considering relevant grooves, transition curves, drill holes etc. Either elastic or elastoplastic material behaviour is assumed depending on each load level. If necessary, viscoplastic material models can also be required. Overall modelling of the component allows to identify critical areas (hot spots) and to obtain reality based results.

This calculation procedure is different from that of the on-line turbine monitoring system. The latter is based on one-dimensional algorithms. Effects exceeding the range of validity of the one-dimensional theory are covered by correction factors which were derived e.g. from appropriate FEM-calculations in advance.

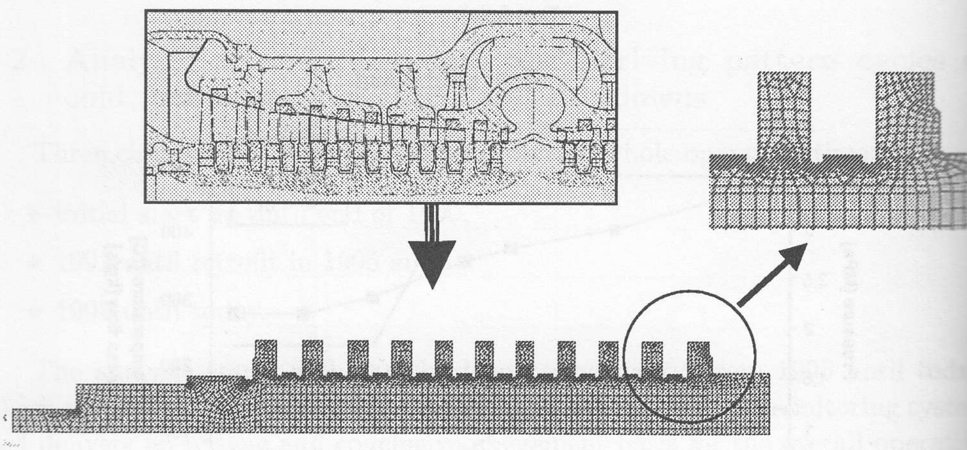

Figure 4. FEM-model of the analysed IP rotor.

The FEM-model of the analysed IP rotor is presented in Fig. 4. Rotor material is the Russian steel R2MA.

Particular attention is directed to modelling of the grooves at the disc-shaft transition as the regions of local stress concentrations. The rotation dominates the mechanical loading. The centrifugal forces of the rotating blades are modelled by surface loads at the outer diameter of the discs.

Boundary conditions for the thermal analyses of the rotor are the steam temperatures and the heat transfer coefficients which are calculated by the Nusselt equations of the particular zones of the rotor surface.

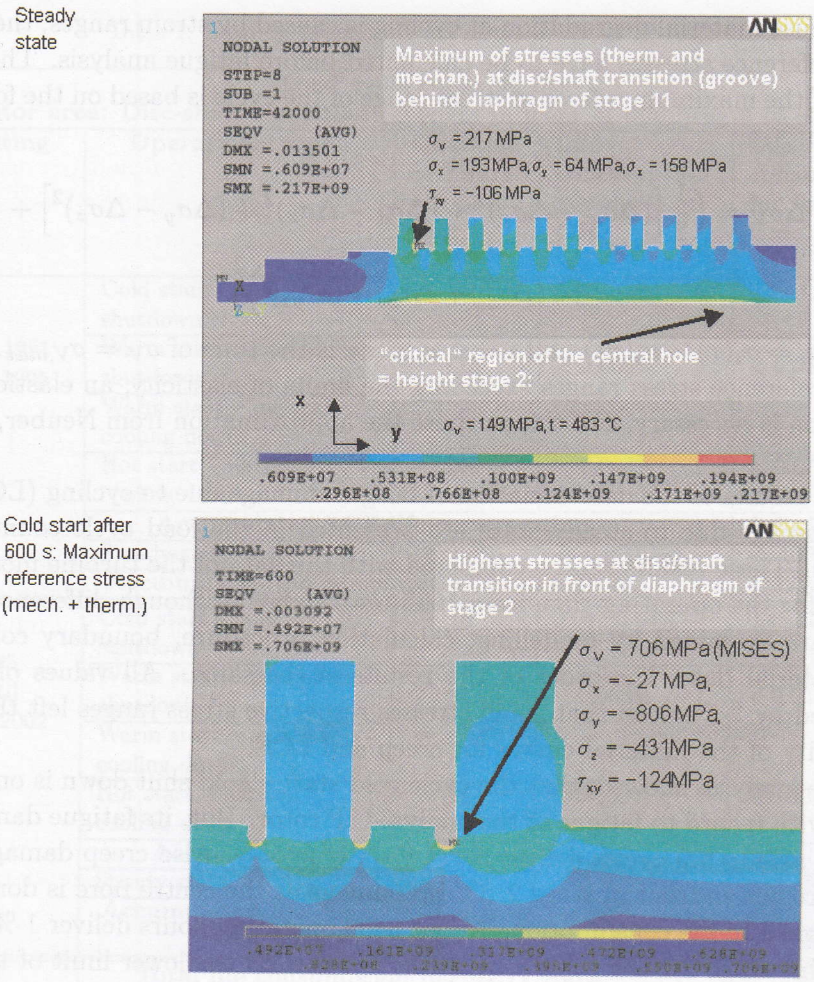

Figure 5. Results of stress analysis of the IP rotor for steady state and cold start.

3.4 Structural and life-consumption analysis of the IP rotor

The structural analysis starts with steady state. As expected, the maximum stresses of the analysed IP rotor are found at the disc-shaft transition behind the diaphragm of stage 11 and at the centre bore, whereas the centre bore in the region of maximum temperature (height of turbine stage 2) is only of interest with regard to creep. However, for cycling the disc-shaft transition in front of the diaphragm of turbine stage 2 is leading with regard to material degradation. Fig. 5 shows the maximum stresses for steady state and cold start as examples. As usual, the thermal stresses are calculated quasidynamically, i.e. the temperature fields of selected time give the body loads for stress calculation.

Because material degradation at cycling is caused by strain ranges, the ranges of the reference stresses have to be calculated before fatigue analysis. The calculation of the maximum reference stress range of the cycle is based on the following equation:

$$\Delta\sigma_V = \Big(\frac{1}{2}\Big[(\Delta\sigma_x - \Delta\sigma_y)^2 + (\Delta\sigma_x - \Delta\sigma_z)^2 + (\Delta\sigma_y - \Delta\sigma_z)^2\Big] + \qquad (1)$$

$$+3\left(\Delta\tau_{xy}^2 + \Delta\tau_{xz}^2 + \Delta\tau_{yz}^2\right)\Big)^{\frac{1}{2}}$$

with $\Delta\sigma_i = \sigma_i(\tau) - \sigma_i(\tau*)$ and $i = x, y, z$. $\tau*$ is the time of $\sigma_V = \sigma_{V,max}$.

At reference stress ranges exceeding the limits of elasticity, an elastic-plastic correction is necessary. For this purpose the approximation from Neuber, e.g. [2] is used.

The results of the determination of fatigue damage due to cycling (LCF) and creep damage due to steady state are presented in the load cycle counting list (Tab. 1). These results can be compared with the data of the turbine monitoring system for the operating time from 1995 until today. Although differences exist, which are explained by modelling, calculation procedure, boundary conditions and material data, the order of the results is the same. All values of Tab. 1 indicated by "<" mean that small stresses respective stress ranges left the limits of validity of the material curves for creep and LCF.

The analyses showed, that the cycle cold start – cold shut down is only of interest with regard to fatigue of the analysed IP rotor. But, its fatigue damage per cycle is small. 100 cycles deliver 3...4 % fatigue only. Also creep damage is low in this region in front of stage 2. Creep damage at the centre bore is dominating with regard to life consumption. About 3400 operating hours deliver 1 % (height of turbine stage 2). But, this assessment is based on the lower limit of the creep rupture strength of the rotor steel according to design rules. Design rules define the theoretical end of life by the lower limit of the scatter band of creep rupture strength, i.e. they assume the material performance of the as built component is equivalent with the weakest material in the scatter band. In most cases the real creep strength is higher, but, unfortunately, unknown. Thus, the material and/or the specific component incorporates a large reserve of creep life. Of course, creep tests can be conducted to investigate the creep strength. However, these tests are expensive and time consuming especially as sufficient representative results are required for a good extrapolation. Only sophisticated calculations, using material data from the specific heat, from NDE and/or information available from certificates of the as received steel condition, are able to reveal these reserves, and to overcome the sometimes considerable conservatism. The Z-Factor-Method [3, 4] is one of the possible procedures. This Z-Factor-Method is based on correlations between creep rupture strength and other characteristics which do not require

Table 1. Load cycle counting list of the analysed IP rotor.

Load cycle counting list Rotor area: Disc-shaft transition (groove) in front of diaphragm of stage 2				
Operating time	**Operational mode**	**Quantity or hours of operation (OH)**	**Life consumption per cycle or OH**	**Life consumption for operating time**
21.03.1981 until 1995	Cold start – cold shutdown	30	0.03...0.04%	0.9...1.2%
	Warm start – partial cold shutdown	115	< 0.003%	< 0.35%
	Warm start – natural cooling down			
	Hot start – natural cooling down	190	< 0.003%	< 0.57%
	Accumulated LCF life consumption			**1.8...2.1%**
	Steady state	100 359	$\ll$ 0.0001%	$\ll$ 10%
	Accumulated life consumption until retrofit			< 12%
1995 until 01.11.2002	Cold start – cold shutdown	15	0.03...0.04%	0.45...0.60%
	Warm start – partial cold shutdown	6	< 0.003%	< 0.018%
	Warm start – natural cooling down			
	Hot start – natural cooling down	11	< 0.003%	< 0.033%
	Accumulated LCF life consumption			**0.50...0.65%**
	Steady state	53 942	$\ll$ 0.0001%	$\ll$ 5.4%
	Accumulated life consumption from retrofit until 01.11.2002			< 6%
	Total life consumption per 01.11.2002			< 18%

additional creep tests. The basis for these correlations are many long term creep tests on different heats with known properties of the as received steel condition, like hardness, short term strength, microstructure, chemical composition etc.. The Z-Factor is defined as follows:

$$Z = \frac{\text{actual creep rupture strength (material, component)}}{\text{creep rupture strength according to the standard (mean value)}} \tag{2}$$

with $Z = 0.8$: lower limit of the scatter band of creep rupture strength,
$Z = 1.0$: mean value -"-,
$Z = 1.2$: upper limit -"-.

The Z-Factor-Method will be applied to enhance the calculations of Tab. 1.

These investigation will be started only after paper submission and the author will present first results in their oral presentation at the conference.

4 Summary and conclusions

Preventive analyses of weak points, life consumption and effects on costs en able VE-G to prepare future operation scenarios of their lignite-fired power plant without taking the risk of decreasing reliability, availability and profitability.

The analyses of a particular 500 MW turbine showed that no adverse effect with regard to forced ageing are expected for cyclic operation. Hence, the turbin is not the critical component of the analysed power plant.

The calculated life consumption fitted the turbine monitoring system dat quite well. The centre bore of the rotor is "leading" with regard to materia degradation. In conclusion the recommendation was given to repeat the boresoni test of the centre bore at the next in-service inspection of the turbine.

The conservatism of the life-consumption analyses will be checked by the Z-Factor-Method, which allows a component specific evaluation of the creep ruptur strength of the rotor material.

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