Enhancing operational flexibility of fossil power generating assets based on non-linear numerical thermo-mechanical damage and fracture analysis

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Abstract: A power generation toggle from the conventional sources to the becoming rapidly prioritisable renewable energy production poses a challenge for the fossil fired power plants. The strong dependency on the weather conditions makes such issues as e.g. non-predictable availability and variable loading to the ad hoc asset management tasks in terms of increasing operational flexibility. The existing fossil power plants were not designed to generate the energy according to the real time demand. The paper focuses on the results of this tendency and their impact on the backbone of all power plants - power plant equipment –suffering from the accelerated accumulation of the combined creep-fatigue damage because of the more and more tightened transient start-up and shutdown conditions, increased heating rates and number of operational cycling. Some practical examples of the remaining life time assessment of the rotating and non-rotating high temperature components based on the computational analysis shows the applicable ways to increase the component life time expectation and, therefore, leading to the noticeable flexibilization of the power plants.

Keywords: Power Plant, Turbines, Crack Propagation, Low-Cycle Fatigue, Creep, Damage, Heat Transfer, Thermal Stress.

1. Introduction

The global modern trend in power generation politics is reduction of carbon emissions. Therefore, the conventional power production, among others with fossil-fired plants, is being throttled and renewable energy sources are key substitutes instead of conventional power plants for electricity generation. The main contributors of the renewable power production are wind and solar plants, see Figure 1 as an example. Various forms of the daily grid feeding are shown for one week from Monday till Sunday (Weber, 2006). The based-load power stations supply the power up to half of the expected peak-load. The peak-load power stations follow the energy consumption course. With the increasing feeding of the wind energy the peak-load power plants were operated in turndown mode until base load power stations would have to be switched off. The generation schedule then would be dependent almost only on feeding of wind energy.

But the renewable power production is strongly dependent on purely predictable local wind and weather conditions and time of the day. As a result, the conventional power plants have to take over the grid demand peeks and to counterbalance the fluctuations of the electricity generation. Such fluctuations can occur more often than once a day. This leads to increasingly frequent operating cycles and to the power plant operations beyond design limits. The flexible operation results in significantly increased amplitudes of the transient thermo-mechanical power plant component loading much less higher fuel costs (start-ups, low load operations), increased wear of steam-heated components.

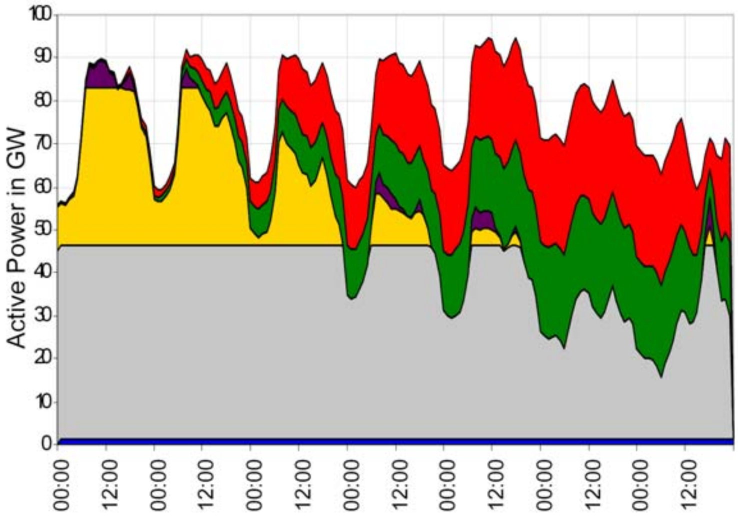

Figure 1. Behavior of the power station park during a week with strong wind power grey: base-load, yellow: peak-load, green: wind onshore, red: wind offshore, blue: run-of-river, purple: pumped storage (Weber, 2006)

The main computational issue is an assessment of the current damage state of in-service exposed components. Only having this detailed information it is possible to determine the reliability and availability of the components for the future safe varying operations.

2. Material Damage Mechanisms

High temperature thermo-mechanical fatigue is a dominating material damage mechanism intensified by power plant operations in flexible regime.

2.1 High temperature damage

The crack initiation process or material rupture in the local region under high temperature operational conditions is assumed to occur due to reduction of the bearing area of this region based on the well known L. Kachanov continuum creep damage mechanics (CDM) approach (Kachanov, 1994). Based on this approach the equation relating the bearing area (bearing capacity) to the operational life under moderate operational load can be quantified in terms of generalized life fraction damage as

$$\Omega_t = \frac{t}{t_r(T,\sigma)}$$

Within this approach the material creep behaviour obeyed the power law relationship mostly used in the practical applications

$$\varepsilon_c = A_c \sigma^{n_c} t^{m_c}$$

can be reformulated by the following equation:

$$\varepsilon_c = A_c \left[\frac{\sigma}{(1-\Omega_t(T,\sigma,t))^d} \right]^{n_c} t^{m_c} \approx A_c \left[\frac{\sigma}{1 - d \cdot \Omega_t(T,\sigma,t) - \frac{d}{2} \cdot (1-d) \cdot [\Omega_t(T,\sigma,t)]^2} \right]^{n_c} t^{m_c}$$

This formalism postulates to describe the microstructural degradation/damage with a single state variable Ω_t causing the accelerating creep. The parameter d mirrors implicitly the ductility reduction (ageing) during the operation time. The “bearing capacity” of the loaded area is reduced by the diffusional creep (bulk and grain boundary transport mechanisms dominating over the dislocation driven mechanism) deteriorating the grain boundaries at constant value of the temperature dependent parameter n_c. The main advantage of this approach is that the additional temperature T, stress σ and time t depending term $1 - d \cdot \Omega_t(T,\sigma,t)$ enriches algebraically the creep strain equation with an additional functional dependence so that it becomes possible to assess the tertiary creep.

The creep strain curves at different applied load levels are shown in Figure 2.

2.2 Creep-Fatigue interaction

In order to take into account the mean stress effect in both the elastic and plastic range the well known Manson model (Manson, 1966) is used:

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f - \sigma_m}{E}(2N_f)^b + \varepsilon_f \left(\frac{\sigma_f - \sigma_m}{\sigma_f} \right)^{\frac{1}{n}} (2N_f)^c$$

The fatigue parameters b and c and n are calculated in the frame of Universal Slopes equations for low alloyed steels. One of the early attempts to provide quick estimations of fatigue life under combined creep and fatigue conditions was the so called “10% rule”, which was considered as a modification of the Universal Slopes equation. This rather conservative approach excludes inherently different influencing factors. To reduce the conservatism of the approach the following formulation considering the life fraction damage Ω_t is adopted:

$$\frac{\Delta\varepsilon}{2} = (1-\Omega_t) \left[\frac{\sigma_f - \sigma_m}{E}(2N_f)^b + \varepsilon_f \left(\frac{\sigma_f - \sigma_m}{\sigma_f} \right)^{\frac{1}{n}} (2N_f)^c \right]$$

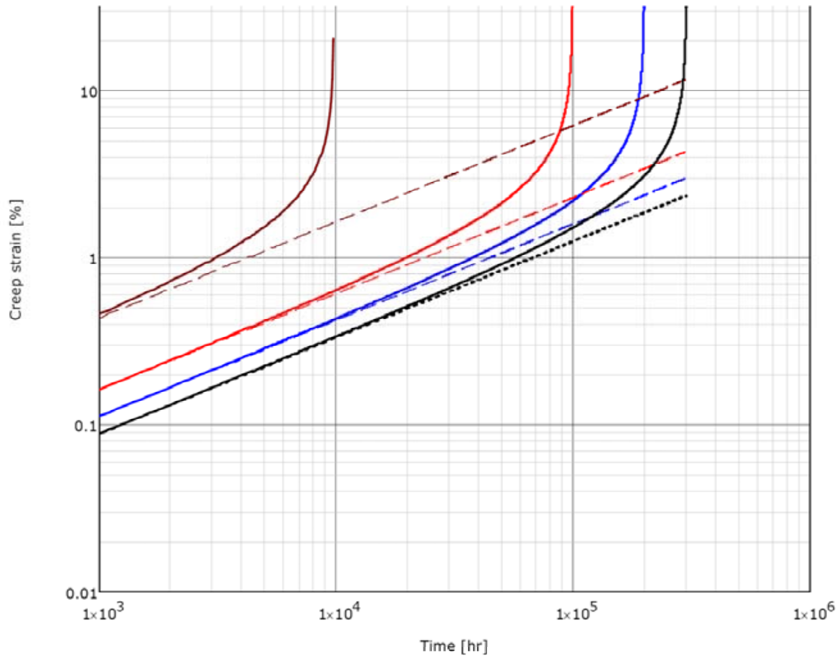

Figure 2. Creep strain curves at typical turbine operating load levels

The growing with the operational time variable $t\ \Omega$ takes into account the negative influence of the intergranular damage in the form of microstructural change, carbide coarsening on the fatigue life curve. Figure 7 demonstrates the affect of the creep damage on the low cycle fatigue curves using the above equation.

2.3 Crack propagation

In the frame of the discussion above the crack growth rate in the thermal ageing structure per cycle is not adequately predictable by the simple summation of the fatigue and creep crack growth portions like

$$\left.\frac{da}{dN}\right|_{Operational\,Cycle} = \frac{da}{dN} + \int_{\Delta t_{Cycle}} [\dot{a}]\,dt$$

(Here an operational cycle is defined as a sequence "start-up → steady state → shut down)

The creep at low stress level does not open the crack, but plays an assisting role by weakening the grain boundaries. The crack opening/propagation takes place at temporary acting high stress during transient power plant operations. These high far-field stresses are x-times magnified at and near the crack tips and lead to the local inelastic (dislocation creep, strain-rate dependent plasticity) deformation. The crack growth can be assessed by the Paris-Erdogan equation with the parameter C modified with the term $1-\Omega_t(T,\sigma,t)$ accounting for the structural local thermal ageing:

$$\left.\frac{da}{dN}\right|_{Operational\,Cycle} = \frac{C}{1-\Omega_t}\left[\Delta K_I\right]^n$$

3. Flexibility improvement

Generally speaking the flexibility of power plants can be considered as a reaction time on the electricity demand or readability to provide energy to the grid as soon as required. For the power plant operator that means to start the turbine fast during prescribed schedule. It is well known, that the shorter the start-up time, the higher arising thermal stresses in the stationary and rotating components. Therefore, the main safety issue is to quantify the level of the thermal stress and its dependency on the temperature rate. The conventional way to avoid or at least to reduce high thermal stresses during start-up is to pre-warm the involved components. For this aim the power plant can be operated in the so called partial load mode.

3.1 Steady state operation mode: Partial load

During periods of low grid demand plants can be operating at minimum load level (20-30% of the rated load limit). It is important to understand the risks that come with such operation:

- Increased vibration of the high, intermediate and low pressure turbine rotors and blades
- Increased solid particle erosion of stationary part like valves and nozzles
- Increased water droplet erosion
- Increased concentration of the water steam impurities causing corrosion
- Increased axial (thermally induced due to exhaust heating) displacement of the low pressure turbine components
- Increased thrust bearing loading

These issues have to be computationally assessed to evaluate the realistic availability of the power plant components. SIMULIA computational packages provide the best tools to simulate, analyze and optimize that operational mode and herewith mitigate the operational risks.

3.2 Transient operation mode: Start-up time reduction

Here we present an example of the thermo-mechanical remaining life time assessment of a high pressure industrial turbine.

Figure 3 shows the three-dimensional CAD model of high pressure turbine and the considered turbine as well as the disassembled and prepared for the non-destructive inspection high pressure turbine.

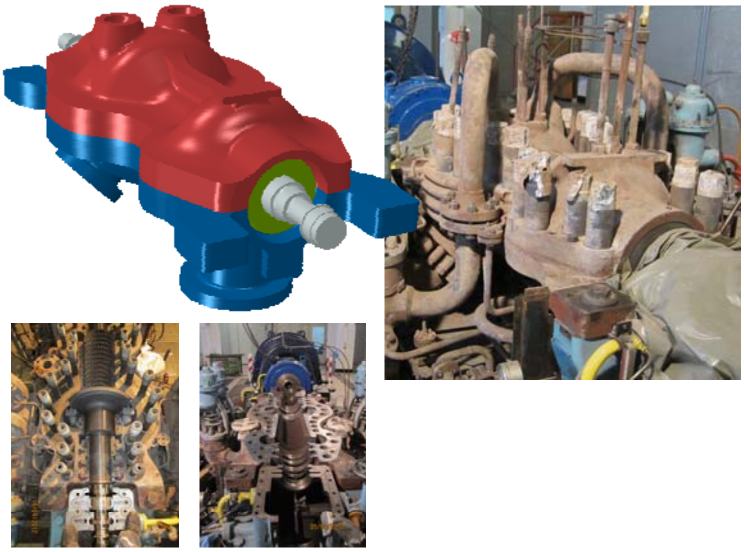

Figure 3. High pressure turbine and its CAD model

3.3 Process data assessment

Identification of the transient and steady state boundary conditions in the transient thermal finite element analysis requires determination of representative temperature curves by an assessment of the recorded operating data. The transient and steady state operational conditions are controlled by the thermocouples which are installed in the stationary turbine components. Based on this information the thermal and mechanical boundary conditions needed for the computational purposes can be obtained. The temperature courses chosen in this way have to reproduce the representative thermal load conditions for the cold start, warm start and hot start operations. The obtained temperature profiles are inputted by a few points. An example of the cold start-up temperature curves and determined temperature profiles are shown in Figure 4.

3.4 Modeling and computation issues

Thermo-mechanical finite element analysis done with Abaqus/Standard is carried out in two steps. Firstly the thermal analysis is performed in order to obtain the temperature distributions in the turbine components at various transient and steady state thermal load cases. Subsequently stress-displacement analysis is conducted with thermal boundary conditions obtained from thermal analysis. A longitudinal section of the CAD model and the distribution of the temperature in the high pressure turbine components at steady state operating condition are shown in Figure 5.

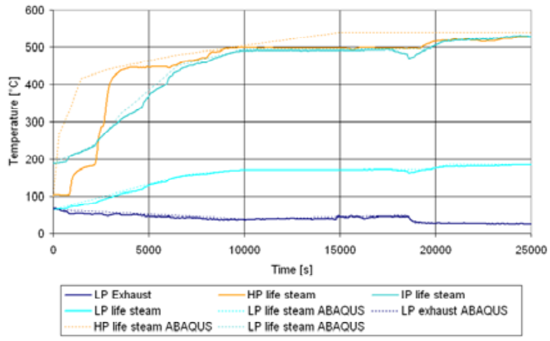

Figure 4. Process data assessment

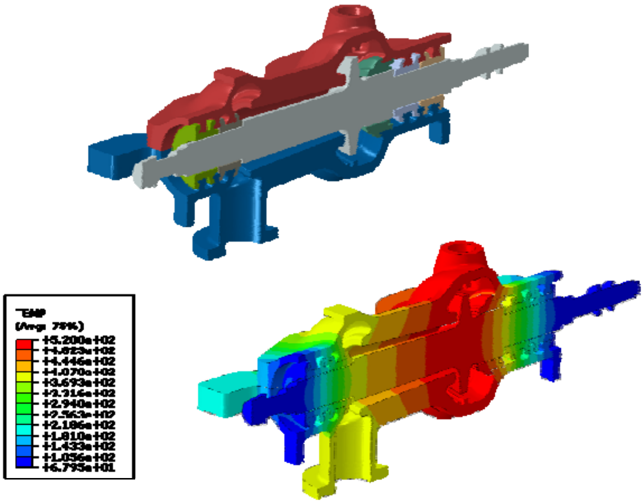

Figure 5. CAD model and a steady state temperature distribution

The transient thermal analysis provides time-dependent temperature distribution in the modeled components. Figure 6 shows the transient temperature field and the corresponding distribution of the equivalent (von Mises) stress during start-up at the time point of maximum tensile load.

3.5 Start-up time reduction

The current state of the life time consumption of the component can be usually analyzed based on the design data compared and verified with the operational data obtained as described in 3.3.

The red line in Figure 7 shows the steam temperature increase which causes the maximum thermal stress values during the initial start-up phase (approx. during first 20 minutes). Under assumption that all start-up procedures were done under the similar conditions, the life time consumption (component damage) up to the assessment time point can be computationally evaluated, s. Figure 8.

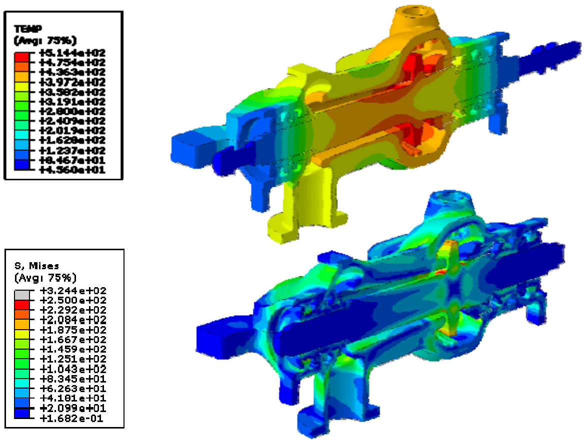

Figure 6. Transient temperature and corresponding equivalent (von Mises) stress distributions during turbine start-up

One of the main consequences of the start-up time reduction is an increase of the thermal stress level. Figure 7 presents two modifications of the transient behavior with the 20 and 40 % higher temperature rates (blue and green lines respectively).
The resulting growth of the damage rate (induced by the increase of the temperature rate) dominantly due to the high temperature low cycle fatigue is shown in Figure 8 as the “Cumulative Damage Modification 1”- and the “Cumulative Damage Modification 2”- curves.

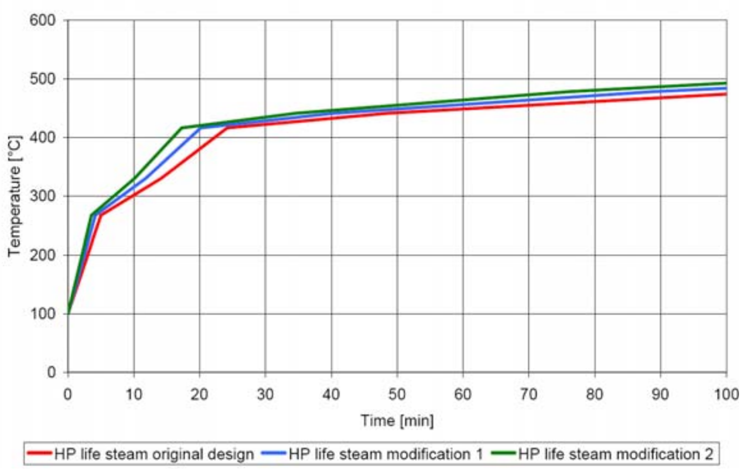

Figure 7. Start-up steam temperature courses

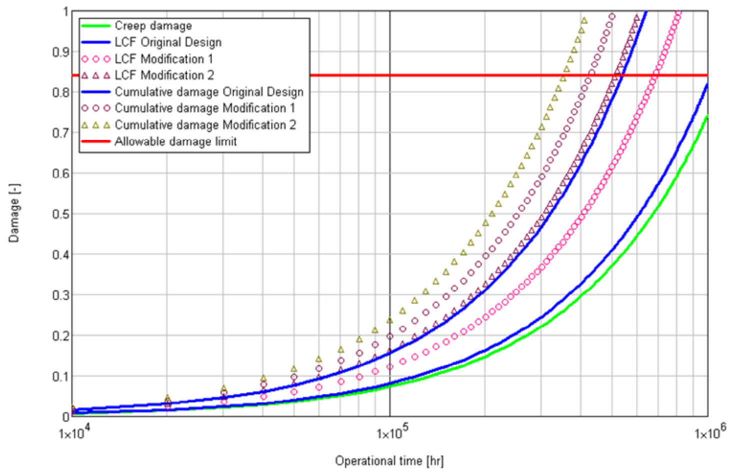

Figure 8. Results of damage assessment

4. Conclusion

Production of the renewable power depends strongly on purely predictable local wind and weather conditions and time of the day. The conventional power plants are forced to take over the grid demand peeks and to counterbalance the fluctuations of the electricity generation. The desirable flexibility of the conventional power plants results in significantly increased amplitudes of the transient thermo-mechanical component loading such as start-ups and shut downs, low load operations and increased wear of the involved rotating and stationary components.

The power plant components designed 15-20 years ago contain in some extent safety reserve regarding optimal choice of the geometry, material and adequate thermal and mechanical boundary conditions.

The modern simulation program packages like SIMULIA enable to compute realistically the in-service accumulated damage of the components, to check some future operational scenarios and to analyze their consequences. The example demonstrated in the paper shows the successful application of the CATIA and Abaqus for the numerical assessment of the availability of the power plant components, reducing on the one hand the intrinsic over-conservatism of the original design and mitigating verifiable the operational risks otherwise.

5. References

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