Steam turbines subject to flexible operation

Frank Biesinger, Huáscar Lorini and Hans-Holger Knauf

Kurzfassung

Dampfturbinen unter dem Einfluss einer flexiblen Betriebsweise

Der Bedarf für flexiblere Kraftwerke ist in den vergangenen Jahren deutlich angestiegen. Aufgrund der Energiewende hat sich das Last- und Betriebsverhalten von vielen Kraftwerken von Grundlastbetrieb hin zu einem flexibleren Einsatz gewandelt. Die Anzahl an Anfahrten, die jährlichen Betriebsstunden und die Änderungsgeschwindigkeiten haben sich alle grundsätzlich geändert. Die Konsequenz für die Komponenten der Dampfturbinen durch schnelleres Anfahren, längere Stillstandszeiten und häufigeren Niedriglastfahrten ist ein erhöhter Lebensdauerverbrauch.

Um die Fähigkeiten für einen flexibleren Betrieb zu ermitteln, muss der gegenwärtige Lebensdauerstatus für die kritischen Turbinenkomponenten bestimmt werden. Die Verteilung der Restlebensdauer für das zukünftige, flexiblere Lastregime ist dann möglich. Die endgültige Implementierung der aktuellen Thermospannungsüberwachung erlaubt dann noch die Angleichung der Einstellwerte, passend zu der neu verteilten Restlebensdauer. Eine größere Anzahl an Betriebszuständen mit erweiterten Schutzkriterien steht zur Verfügung zur Unterstützung der neuen Herausforderungen für die Dampfturbine.

Weitere Möglichkeiten zur Steigerung der Flexibilität ergeben sich z.B. durch die Rekonditionierung eines existierenden Rotors mit besonderem Blick auf die erste Schaufelnuteindrehung. Damit könnte der Lebensdauerverbrauch deutlich zurückgesetzt werden. Eine weitere Alternative stellt auch der Ersatz einer Komponente durch eine mit höherwertigen Eigenschaften dar. Der resultierende Einfluss auf den Lebensdauerverbrauch wird besprochen.

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Introduction

Typical design features of reaction steam turbines

The key technical features of a typical reaction steam turbine comprise several items proven by service operation. The welded rotor, introduced in 1930, enables stress reduction during thermal transients for faster and more frequent load cycling capabilities as well as an appropriate material selection based on the design requirements. The shrink ring design facilitates a rotationally symmetric inner casing resulting in reduced wall thicknesses ensuring flexible operation. A single bearing design for multi-casing turbines makes possible a shorter overall turbine shaft length and reduced shaft alignment time. The longer LP last stage blades deliver increased efficiency and a robust design with stress-enhanced grooves for higher reliability. The advanced blading delivers higher efficiency based on a three-dimensional profile design. A typical reaction steam turbine is shown in Figure 1 [1].

Flexibility requirements

The demand for more flexible modes of operation from conventional power plants has increased significantly during the last couple of years. The typical mode of operation for bituminous coal units for example has shifted from a more base-load oriented regime towards cycling operation. This is due to the increasing influence of fluctuating renewable energy production, imposed by the "Energiewende" (turnaround in energy policy) especially in Germany. Figure 2 shows the overall increase of the share of renewable energy production between 2011 and 2020 [2].

Consequences of this trend are depicted in Figure 3. Besides the increasing number of starts, there will be a demand for faster start-ups and increased load gradients. Additionally, the minimum load for stable plant operation has to be reduced to allow for low load operation. At a bituminous coal-fired power plant in Germany, an optimisation of the mill strategy to single-mill operation enables stable low-load operation at 15 % [4]. This reduction of the minimum load for stable plant operation is also required for the future development of the energy market [5].

The changing market conditions for steam power plants lead to the development of certain tools comprising hard- and software packages, also suitable for retrofit. This portfolio of flexibility products, originating mainly from combined cycle power plants, consists of five packages, Start, Perform, Respond, Reserve and Care, and

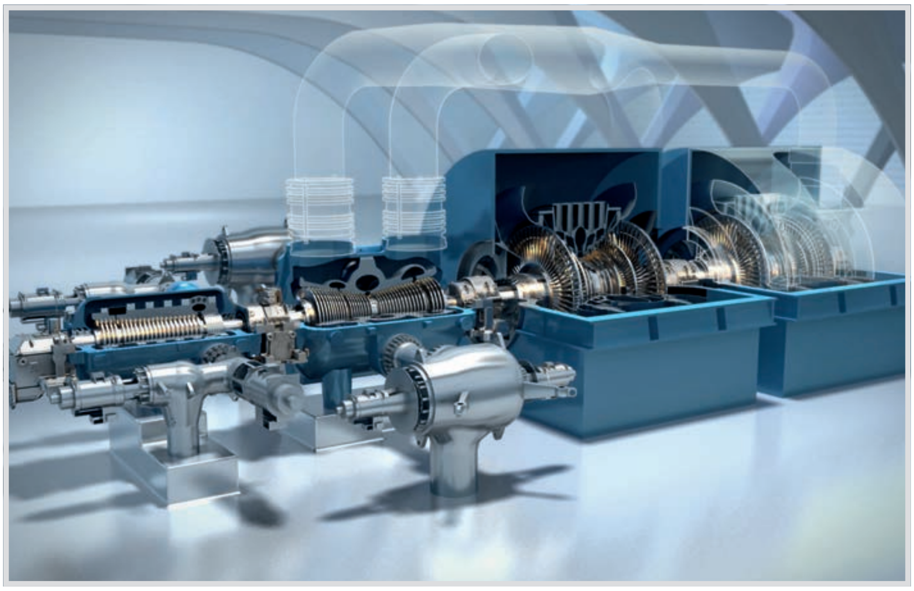

Fig. 1. Steam turbine incorporating reaction type blading [1].

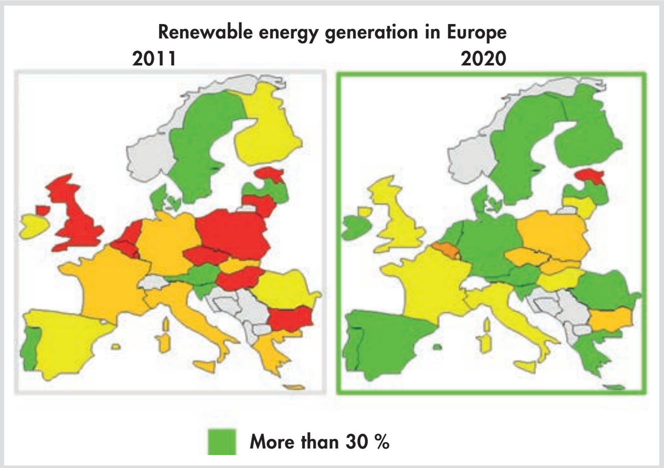

Fig. 2. Share of renewable energy production 2011 to 2020 [2].

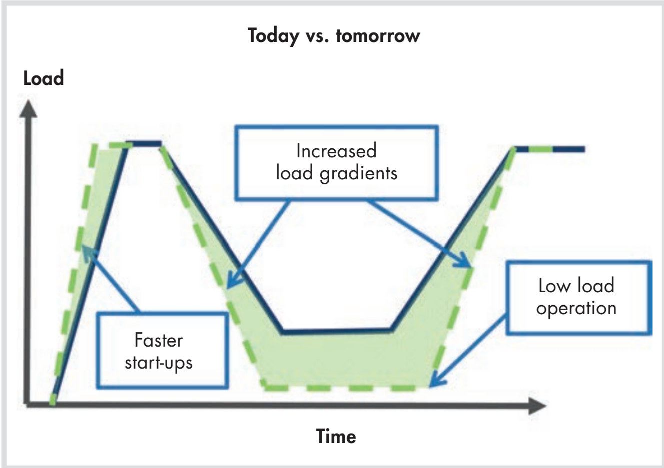

Fig. 3. Flexibility requirements for thermal power plants [3].

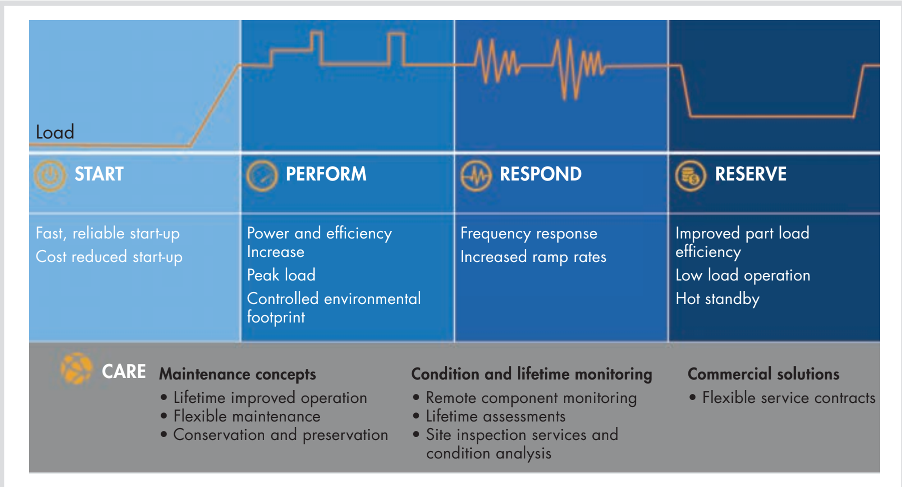

Fig. 4. FLEX SUITE™ for steam power plants [6].

is known as "FLEX SUITE™". The main algorithms from this tool suite are, of course, also applicable to conventional power plants as shown in Figure 4. In a market where the value of operational flexibility is becoming much more important, the "FLEX SUITE™" packages can support the ability of the power plant owner to compete in this market [6].

Impact on lifetime

Changes in the start-up behaviour of thermal power plants result, very often, in an increase in the steam- and metal-temperature transients during start-up. The effect of higher transients during low-load operation or shutdown should not be neglected. The steam turbine is started with a certain temperature distribution across the main components resulting from the operation mode immediately prior to the start-up. This leads to a differentiation of the various types of start-up, such as cold- or warm-start. By contrast, the steam temperature during start-up of the steam turbine is determined by the capabilities of the boiler system and the requirement to deliver super-heated steam to the turbine components. This results in a higher steam temperature, compared for example to the surface- or metal-temperature of the turbine rotor. By focusing on the outer rim of the rotor, and in particular the first blade groove, it becomes apparent that during start-up compressive stresses evolve (cf. Figure 5). These compressive stresses originate from the thermal expansion of the surface, which cannot expand freely due to the rigid connection to the centre of the rotor. After reaching nominal or steady-state conditions the steep thermal gradients subside and moderate tensile stresses, emanating primarily from centrifugal forces come into being. During shutdown the situation is reversed. The steam temperature is very often reduced, causing the surface to contract. This contraction process gives rise to tensile stresses. Similar effects occur during load changes.

The stress range lying between the peak compressive and peak tensile stresses combined with a certain reference temperature gives rise to the number of cycles to crack initiation (Na) under low cycle fatigue (LCF) conditions. Figure 5 (on the right hand side) depicts a steam turbine rotor with the area of the first blade groove enlarged. The circumstances giving rise to alternating stresses, as previously mentioned, take place at this location. The view of the blade groove indicates the result of the LCF assessment. The red colour implies a low number of Na. In this case crack initiation has been predicted taking into consideration actual operational behaviour. An existing crack is therefore visible at the place indicating high LCF damage. It becomes apparent that during load changing operations, increasing the number of start-up and low-load cycles or imposing steeper thermal gradients results in increased LCF damage accumulation. To some extent, the

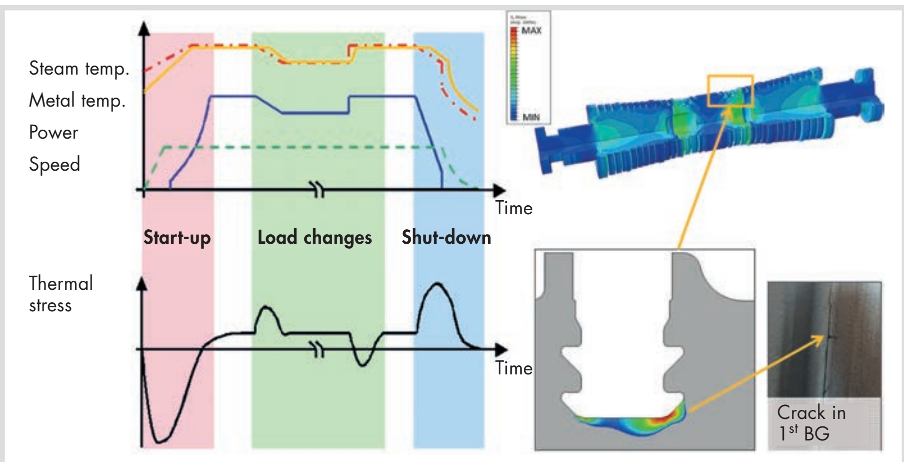

Fig. 5. Transient operation with evolution of thermal stresses and impact on first blade groove.

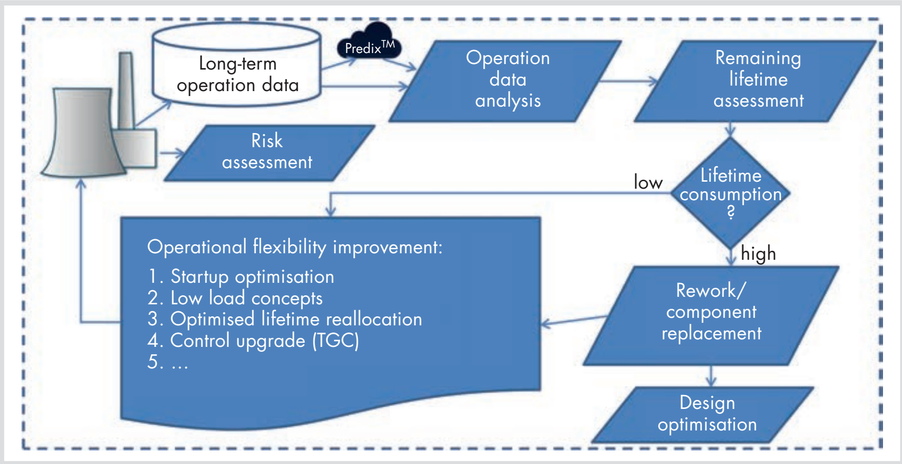

Fig. 6. Lifetime Management.

cost attributable to increased flexibility is an increase in lifetime consumption.

Assessment of lifetime and flexible operation

Remaining lifetime assessment

More flexible operation can lead to an increase in lifetime consumption. To quantify this increase and to determine the overall lifetime expectancy, a remaining lifetime assessment (RLA) has to be carried out. This can be done in accordance with the Lifetime Management Cycle shown in Figure 6. An initial, probably rough, assessment could be a risk assessment. This can be carried out in accordance with VDMA 4315-5 [7] for example, and leads to a first insight into possible areas for improvement. The Lifetime Management Cycle commences at the power plant recording real-time operating behaviour including long-term storage of operating data. The analysis of operating data can be performed directly using appropriate software tools or via the cloud based Predix™ [8]. The goal of the operating data analysis is to determine the number of events, e.g., start-ups to clarify the actual operating behaviour. Additionally, all necessary transient heat transfer input data for the steady-state and transient Finite Element analysis are provided automatically.

The next step is the RLA itself. The scope of the RLA comprises two parts. The first part is the non-destructive testing (NDT, cf. Figure 7) and the second part is the theoretical RLA. NDT is an effective means of determining the actual status of material degradation under the influence of real-time operating conditions. Primarily two effects are investigated during the course of a RLA, creep- and LCF-damage. The evolution of creep damage at accessible surfaces can be quite easily monitored by means of the replication of the microstructure. Various stages of material damage can be distinguished. A correlation between the evolution of creep damage, microstructural material evolution and

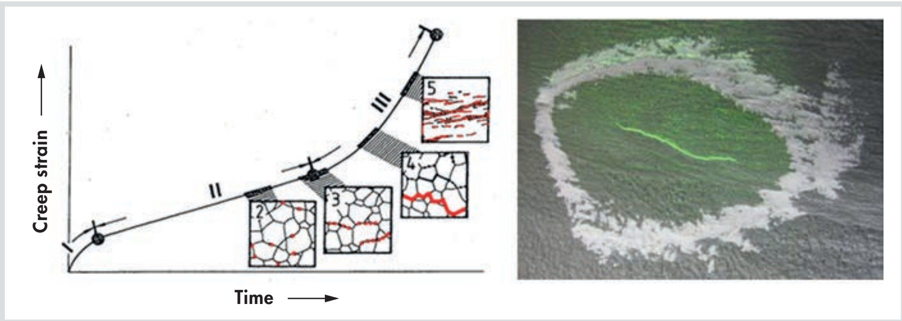

Fig. 7. Results of non-destructive testing, (left) creep-damage, (right) LCF-damage.

relative remaining lifetime is available for selected materials [9]. The determination of evolving LCF-damage prior to crack initiation is technically not feasible. Only damage with cracks of a certain size can be detected either by surface crack inspection or ultrasonic testing. This results in non-conservative results for rotors in terms of crack initiation at surfaces.

The theoretical part of the RLA determines the amount of LCF- and creep-damage based on the analysed operating history. State of the art methods such as the Finite Element Method (FEM) including advanced transient heat transfer models and recognised material models are used. The total damage is assessed using methods such as the linear life fracture rule. The outcome is the remaining lifetime evaluation taking into consideration the operating-history and future operating regime. Using the theoretical calculation it is possible to determine the point in time at which crack initiation of the rotor can be expected to commence. This is advantageous when compared with the pure NDT approach which only covers the conditions as found.

Using the methods described above it is possible to provide answers to questions concerning the amount of lifetime consumption. Low values of lifetime consumption allow the possibility to carry out a start-up optimisation or to implement a low load concept. High values of lifetime consumption require corrective action otherwise operation within a regime with unknown safety margins may take place. At certain locations, for example at the first blade groove of the rotor, a rework can be performed to remove the damage or pre-damaged material. In some cases the entire replacement of a component may be recommended.

The customer specifies the number and share of the different operating modes over the entire lifetime of a new unit. This results in a planned lifetime. Based on the predicted lifetime consumption of a power plant in service, resulting from a RLA, the available remaining lifetime could be re-allocated for future operation. This re-

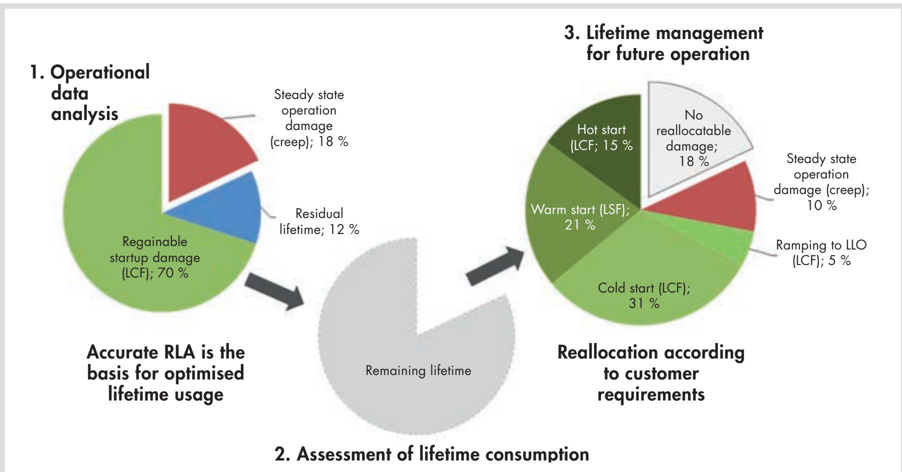

Fig. 8. Advanced lifetime re-allocation [10].

allocation could be adjusted in such a way, so that the progressive lifetime consumption in future fits better to the current and planned operating mode of the plant. This could be combined with an optimisation of the start-up and shutdown behaviour. Figure 8 depicts the steps to be taken for a re-allocation of available remaining lifetime for an arbitrary plant. This plant was designed originally as a base load unit, but for future operation covers peak load during the day and shuts down during the night. The first step is to determine the present condition of the rotor by means of a lifetime assessment. The assessment reveals 88 % of the lifetime at the first blade groove has already been used up. Due to the high lifetime consumption, it was decided to rework the rotor. The rework repairs, at low cost, the start-up damage, and regains the largest portion of the remaining lifetime, but will not regain the lifetime lost due to creep occurring during steady state operation. In our example, the rework at the critical location recovered 70 % of the original rotor lifetime. The reworked rotor geometry includes a stress reduced contour allowing even higher thermal gradients than the original rotor geometry. The rework shifts the critical location in terms of lifetime consumption to the next critical spot [10].

The re-allocated lifetime for future operation is shown on the right hand side in Figure 8. The different amounts of lifetime consumption for steady state creep, the various start-up classes (cold-start, warm-start and hot-start) and these days also load changes are redistributed. A simple reapplication of the original lifetime allocation scheme is inadequate, since the operating scheme of the example unit has completely changed. Instead, the size of each tranche of lifetime should be adapted to the expected future operation mode. The reduced capacity factor allows a reduction in the lifetime provision to be allocated to steady state creep. On the other hand, the increased number of starts requires higher provisions for more low cycle fatigue LCF lifetime[10]. Hence under consideration of above boundary conditions an optimum could be found to maximise the remaining rotor life for its future intended operation in a most flexible mode.

Rework concept

Progressive transient operation may lead to the accumulation of LCF-damage. Depending on the location and the severity of the damage, a rework concept can be applied. An example of such a rework is depicted in Figure 9. The instigation of the rework resulted from carrying out a RLA. The point in time at which the theoretical life was expended was determined and the recommendation to carry out rework at this point in time was given. The rotor was sent to the service factory in Berlin. The

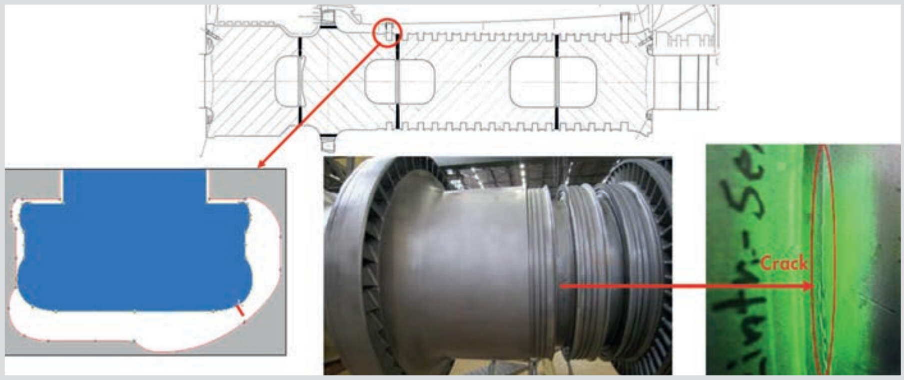

Fig. 9. Rework of an HP rotor.

rotating blades from the respective stages were removed and a magnetic particle inspection revealed crack like indications. A metallographic investigation of samples removed during turning operations confirmed the findings to be cracks. A stress optimised contour at the location with the highest thermal stresses was developed and applied to enable increased flexibility (cf. Figure 9, lower left hand side). The rotor material containing the crack and some material ahead of the crack tip was removed (white collared area). The rework enabled the LCF-damaged material to be removed and regained this portion of the life time.

Thermal supervision of steam turbines leads to more flexibility

The thermal supervision of reaction steam turbines started in 1960. The first com-

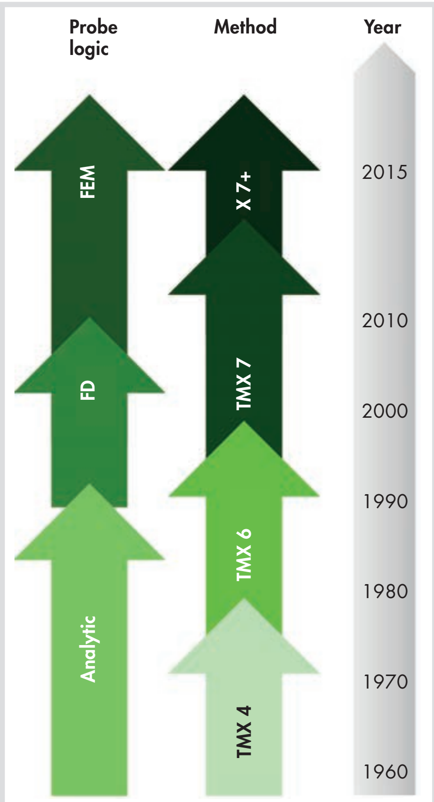

Fig. 10. Timeline of the thermal supervision of reaction steam turbines (TMX).

mercially available solutions were based on a temperature difference of a specially shaped device with a fixed location of the thermocouples. This device was placed in the steam inlet region of the steam turbine and in direct contact with the respective steam conditions. The supervised temperature difference between the surface and the “rotor centre” were measured with hard-wired thermocouples. Analytical methods were used for the determination of the allowable temperature differences. The application was used and designed primarily for base load units to prevent excessive thermal stresses during start-up.

Starting with the next generation (TMX6) a design change was made. The design change meant that the temperature probe was effectively only a thermocouple measuring the near-surface temperature in the inlet region. The transient temperature profile was calculated using the measured temperature as an input and the calculated thermal stresses as an output. Based on the technical knowledge available in the 1980s, only a smooth cylinder as a model for the rotor was used. To calculate the allowable thermal stresses numerical methods, such as the finite difference method (FD) were introduced. The load regime for those units was predominantly base load.

A considerable step forward was undertaken with the development of the TMX7. The new features of this thermal supervision were, for example, consideration of the blade grooves in the rotor and the possibility to account for the desired load regime for future operation. The amount of LCF-damage, arising from the desired load regime, was used for the first time to determine the stress limits (allowable thermal stresses during start-up and shutdown). This thermal supervision enabled a major step forward towards flexible operation. The latest generation of thermal supervision (TMX7+) was released in 2015. This system makes use of the FEM to provide the best representation of the rotor and its physics to calculate the stress limits for various operation modes, such as start-up, shutdown, steady-state and low-load operation. In addition to enhancements of the

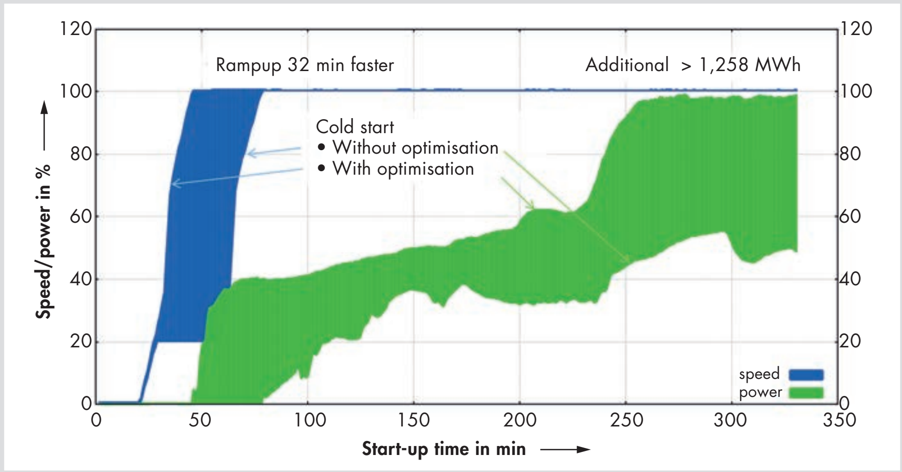

Fig. 11. Example for start-up optimisation of a cold start [11].

calculation algorithm, additional operation modes and major stability improvements in the logic of the turbine controller have been realised. Further, deficiencies in the temperature probe have been resolved and a new probe design with improved measurement accuracy has been developed. The current thermal supervision system enables the lifetime management, as depicted in Figure 8, to be fully supported. The flexibility requirements demanded by owners/operators of steam turbines in the current market environment can be achieved with this type of thermal supervision.

The application of the new thermal supervision, including a control upgrade, is shown in Figure 11. The figure depicts a cold start-up with and without optimisation. The example used is based on an optimisation of a cold start-up at a 750 MW coal fired power plant.

Three major achievements can be demonstrated:

- elimination of the hold speed reduced the time from roll-up of the turbine to nominal speed by 32 minutes;
- the load gradient after synchronisation could be increased;
- an additional 1,258 MWh could be generated.

A further possible enhancement of the start-up behaviour, related to the improved thermal supervision is depicted in Figure 12. It consists of three start-up modes; eco, normal and fast and a further subdivision of the cold start into very-cold (VCS) and cold start (CS), as well as warm start into cold-warm (CWS) and hot-warm start (HWS). The different start-up modes provide a gain in flexibility and the choice of the utility to adapt to market needs in terms of different start-up rates. The freedom of this choice has its costs in terms of lifetime consumption. The higher the start-up rate or shorter the start-up time, the higher is the lifetime consumption. This is clearly visible in Figure 12 by the slope of the curves, except for the hot start (HS).

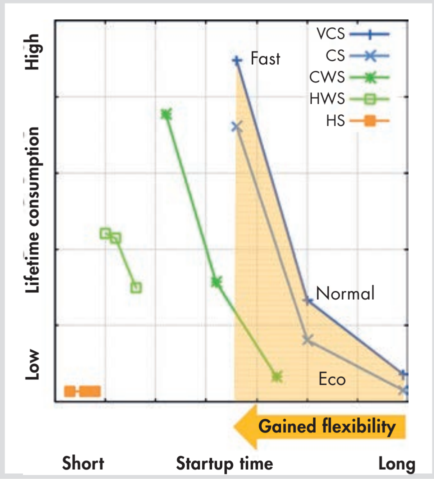

Fig. 12. Influence on start-up time and lifetime consumption.

In this example the lifetime consumption for the HS is almost independent of the start-up mode.

Further options for increasing flexibility

There are also options to enhance flexible operation within an existing steam power plant. Reconditioning of the existing rotor with particular focus on the first blade groove can virtually reset the lifetime clock.

A further alternative may be to replace an existing component with one delivering superior properties. With proper design and material selection, start-up and ramp-up flexibility gain can be achieved. The best solution can only be determined by close cooperation between the utility and the supplier and may require several iterations. The cost impact of superior solutions needs to be considered versus lifetime impact of the assumed future operating conditions. Thus a proper future load and cycling prediction is essential for the final choice of a solution. On the other hand, the final choice of a solution adversely influences future flexibility of operation and could widen the operating regime influencing the merit order of the plant.

Figure 13 shows the results of a study involving the variation of the turbine rotor design and material selection. The baseline chosen for the investigation consists of a monobloc rotor made of 1 % Cr-Steel. During start-up, for example a CS, a soak time is necessary to control lifetime consumption which is detrimental to the start-up time. The first variation focused on the design. The monobloc rotor was replaced by a welded rotor consisting of two smaller rotor forgings introducing a cavity. This change in the design has a big influence on the achievable start-up time, which is shown qualitatively on the right-hand side of Figure 13. Additionally, a change in the material of the hot rotor forging has been investigated. The 10 % Cr-Steel with its superior material properties reduces the start-up time even further. The gain in flexibility is depicted by the orange shaded area and has to be balanced against higher manufacturing and material costs.

In order to improve start-up behaviour, another approach is essentially to avoid cold start conditions and ensure temperature uniformity across the cylinder. Moving from cold to warm or hot start-up conditions has a positive influence on the

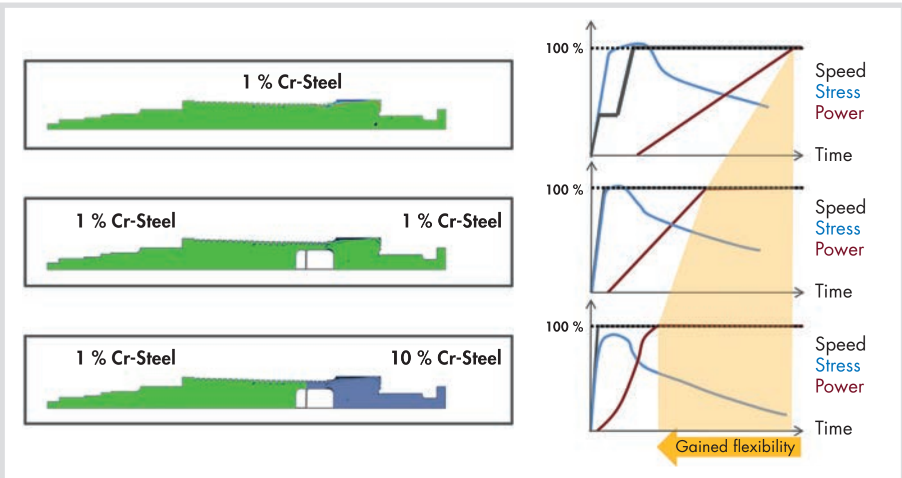

Fig. 13. Flexibility gained by design and material selection.

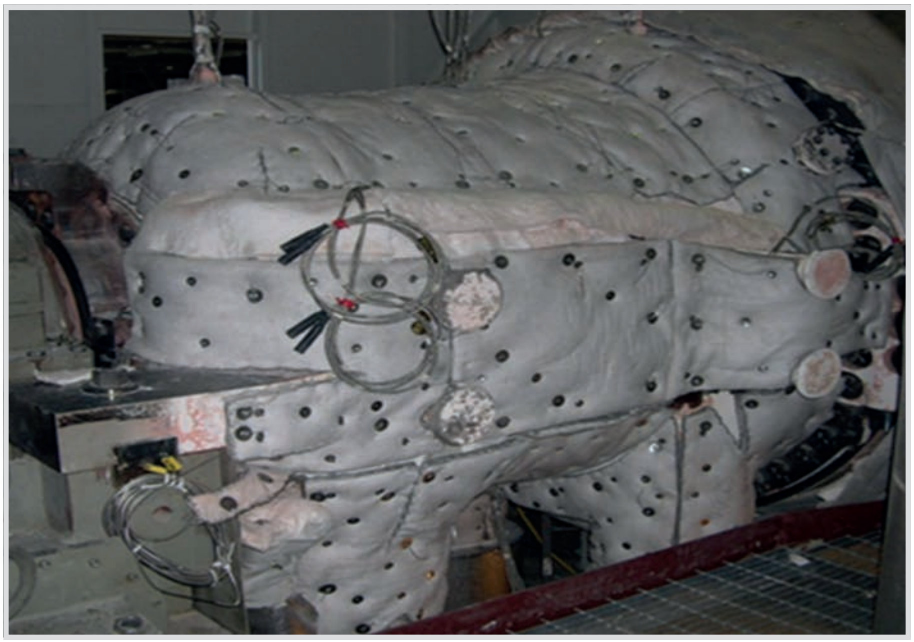

Fig. 14. Shell warming system providing faster steam turbine start times.

lifetime consumption of components. GE's portfolio includes two active heating products:

- Heating blankets
- Hot air heating to warm start conditions

The heating blanket system is available for GE single shell steam turbines as a shell warming system. This solution eliminates cold starts and can deliver a significant reduction in start-up times of typically 30 minutes to one hour. Based on their extensive fleet knowledge, GE has developed a robust system that allows flexibility during start-up by balancing the temperature difference between the upper and lower casing and thus avoid unwanted bending of the shell [12].

Hot air heating is designed specifically for low and medium cycling plants. Hot dry air is injected and circulated within the turbine (with minimum auxiliary power consumption) in order to warm the machine or to retain the temperature above a certain target temperature level in the heat conservation mode. This avoids cold starts with associated thermo-stress initiation and improves the start-up time and cost by actively retaining or establishing a warm condition. The comparison of temperature retention in heat conservation mode versus the natural cooling curves is given here [11]. This provides an indication of when it is beneficial to install this system based on the average shutdown time of the plant. The warm up time is also shown.

As a package included in the flexibility suite for combined cycle plants, this solution can reduce the start time of, for example, a KA26 plant by typically 30 minutes depending on plant specific condition [12].

The system is implemented into the DCS to allow full automation and adds another major advantage, the preservation feature. It avoids corrosive conditions in the steam turbine during stand still.

GE Digital

Understanding that the overall plant performance goes beyond the flexibility of the individual components into a complex interaction between technical boundary conditions and commercial evaluations, GE has initiated a transition into digital power generation. The solution is based on a modular concept with a cloud based platform called Predix™ [8] similar to a well-known Operating System. Indispensable features such as Cyber Security build upon the foundation for a variety of applications that can be added to cover the needs of the client. This allows the combination start-up optimisation and turbine supervisory systems to be linked with the overall plant performance and commercial evaluations. A client will not only be able to ramp up or load his asset faster but will also be able to attribute a cost to it. Costs can have multiple facets such as an influence on lifetime consumption or even tuned inspection intervals for a minimum and controlled down time. Hence the options in a digital power generation are seemingly endless and require the close interaction between the utility and the supplier for individual optimised asset performance.

Summary

The „Energiewende" has changed the market conditions for power plants. More flexibility features, such as faster and more frequent start-up or low load behaviour are required for future operation. The adverse effects, such as pronounced LCF-damage, can be predicted with the remaining lifetime assessment. This is also the basis for the design of future operation with tailored start-up conditions or recommendations for rework and even replacement of components. Excessive thermal stresses can be prevented under consideration of the actual thermal supervision system. Enhanced operation modes in the turbine control system with different start-up speeds, preheating capabilities and the entire digital world are supporting the participation in the current market environment. Specific design features for the turbine rotors or high pressure inner casing will additionally enhance the flexibility.

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