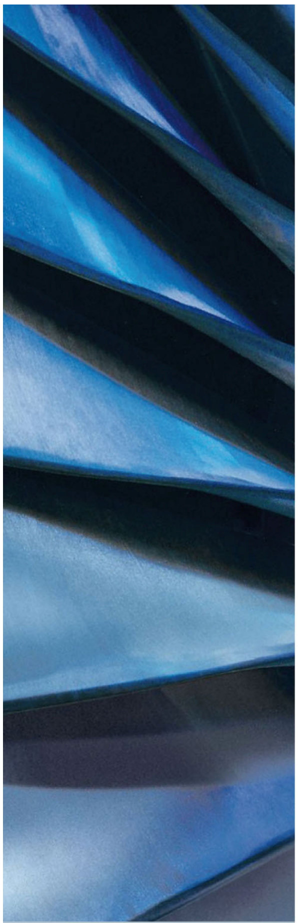

Operational Flexibility Enhancements of Combined Cycle Power Plants

Dr. Norbert Henkel,
Erich Schmid and
Edwin Gobrecht

Siemens AG, Energy Sector
Germany

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1 Abstract

High operational flexibility – the ability of a power plant for fast start-up and to adjust load output fast and predictable to changing market requirements – is an essential prerequisite to ensure economic success in a liberalized market. The paper describes upgrade opportunities for combined cycle power plants, which were originally built as base load plants and are now - due to changing market conditions and fuel prices - forced to operate as peak load plants or as cycling plants with daily start-up.

Major factors limiting the load output of an existing combined cycle power plant are the allowed pressure and temperature transients of the steam turbine and the heat recovery steam generator waiting times to establish required steam chemistry conditions and warm-up times for the balance of plant and the main piping system. Those limitations also influence the fast start-up capability of the gas turbine by requiring waiting times compared to a simple cycle start-up.

The authors' company provides solutions to address all these limitations. For example, the use of final stage heat recovery steam generator attemperators and associated controls to adjust steam temperatures to steam turbine requirements independent from gas turbine load; stress monitoring systems for the thick walled components in the steam turbine and the heat recovery steam generator with different start-up modes for flexible use of component life; optimized main steam line warm-up systems; condensate polishing systems and flexible steam purity requirements; to name only a few.

The steam turbine start-up is modified to allow an early roll off and fast loading – the so called "start-up on the fly". Here, the steam turbine is rolled off with the very first "cold" steam produced in the heat recovery steam generator with full pressure and temperature transients. With these upgrades a start-up time of less than 40 minutes is possible for a 400 MW combined cycle power plant after an overnight shutdown.

2 Introduction

Existing power plants must cope with the challenges of liberalized and deregulated markets. Further on, the compliance with increasing environmental requirements is gaining more importance. Looking closer to the requirements of a power plant in modern power markets, operational flexibility becomes a major topic.

Operational flexibility comprises:

- Fast start-up and shutdown
- Fast load changes and load ramps
- High start-up reliability and load predictability
- Frequency control and ancillary services.

Drivers for this demand are risks like fluctuating fuel and electricity prices. Additionally, a flexible plant opens up new business opportunities like utilizing hourly and seasonal market arbitrage, participation in ancillary energy markets or peak shaving.

An operating profile optimized for these market circumstances increases the economic value of the plant. Depending on seasonal load and the dispatch rank of the plant, driven by competition and fuel prices, it is likely that the plant will be partly operated as base load unit and partly as cycling unit over its lifetime. Therefore, a plant needs advanced cycling capabilities and highest efficiency at base load.

Fig. 1: View of a SCC5-4000F single shaft combined cycle power plant.

Typically, combined cycle power plants built in the 1990s and early years of the new millennium were designed as base load plants with focus on highest efficiency and low initial cost. Due to the significant increase in gas prices and changing market conditions in deregulated markets many combined cycle power plants are now being operated in intermediate or even daily cycling mode. The current plant and control design may not fully support these cycling conditions and the requirements on start-up performance and times.

The authors' company provides upgrade solutions for existing plants to meet these market requirements which are based on the latest and proven cycling plant developments for new units.

3 Plant Design for Fast Cycling

Most of the existing combined cycle power plants were initially designed for base load operation due to low fuel prices in the nineties resulting in low electricity costs. Nowadays, many operating combined cycle plants are shifted to intermediate load and new plants are specified for cycling load regimes because of today's high gas prices. Therefore, features for high operational flexibility like short start-up and shut-down times are emphasized by customers.

3.1 Cycling Plant Design Features

As an answer to the changed market requirements, Siemens has developed a fast start-up concept and implemented it into the reference power plant design for new units. With this design, a reduction of the start-up time of more than 50% can be achieved after an overnight shutdown. Additionally, the start-up times after a weekend outage shutdown (64 hours) and an extended outage shutdown (more than 120 hours) were also significantly reduced.

To achieve this cycling capability, some new features have been introduced in the plant design:

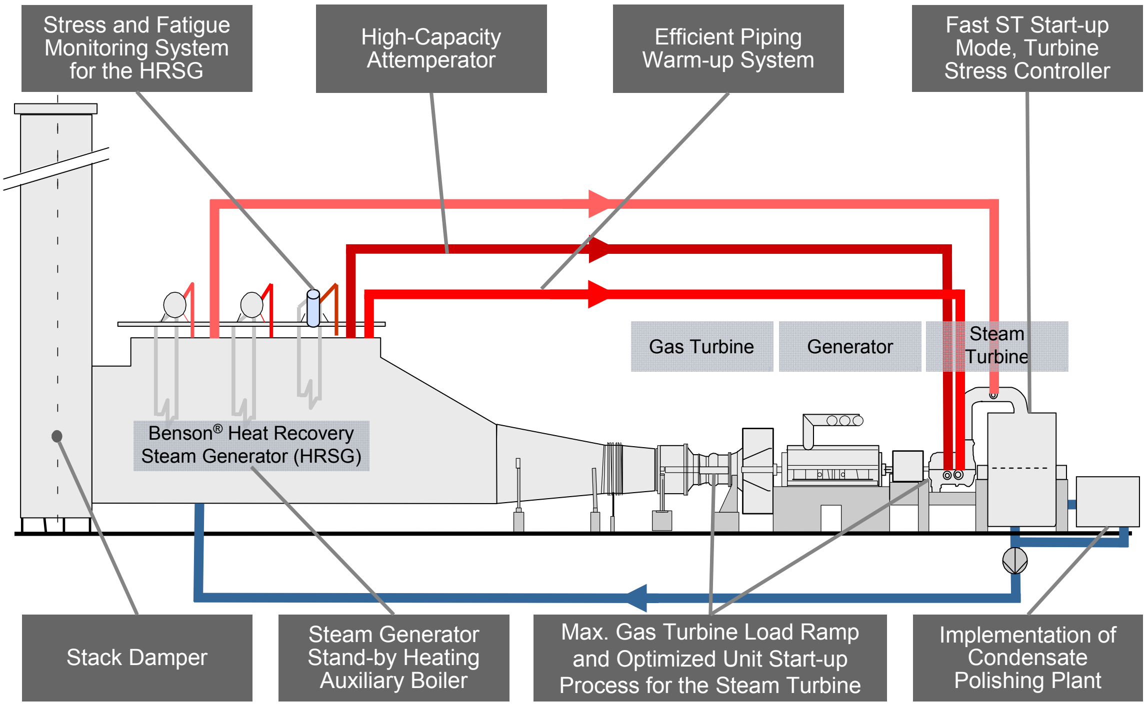

Fig. 2: Plant design features for fast cycling.

- **BENSON® Heat Recovery Steam Generator** with evaporator steam sparging, stack damper, optimized superheater outlet header and manifold design. This steam generator design eliminates the thick wall high pressure drum and allows an unrestricted gas turbine start-up including a high number of fast starts. The implementation of a drum type boiler is also possible, but may lead to increased start-up times or high lifetime consumption.
- **Condensate Polishing Plant** to eliminate the waiting time for steam purity chemistry.
- **Improved Steam Turbine Start-up Sequence** incorporating the **Turbine Stress Controller** for fast, load orientated start-up.
- Two stage **High-capacity Attemperator** in high pressure and hot reheat steam lines to adjust steam temperature to steam turbine requirements.
- **Modified Unit Control** to take advantages of maximal gas turbine load ramp.
- **Auxiliary Boiler** providing low pressure steam used for the steam generator evaporator steam sparging and steam turbine seal steam supply.
- High level of **Automation** including fully automated drains and vents that allow a fast and reliable start-up without operator interferences.
- **Mechanical Vacuum Pumps** instead of steam jet air ejectors to evacuate the condenser before gas turbine start-up and keep it evacuated during plant standstill.

A key element to optimize the complete unit start-up process and to significantly increase the load output during start-up is the use of final stage high capacity attemperators in the main and reheat steam lines. The steam turbine needs steam temperatures of a certain value above metal temperature. The steam temperature can be adjusted through the variation of the gas turbine exhaust temperature – through variation of the gas turbine load – as often done in existing base load plants. For cycling plants, this is not beneficial due to the obvious limitations in operational flexibility and the high gas turbine emissions in part load. Therefore, the adjustment can be done by two stage high capacity attemperators which allow a temperature reduction to steam turbine requirements even at gas turbine base load. That means the final steam attemperators allow to decouple the gas turbine from the steam turbine start-up. The main effect is, that the load output of the steam turbine can be significantly increased during start-up by keeping the steam temperatures constant during loading. Steam turbine loading is mainly limited by allowable temperature transients, not by pressure or mass flow transients. A potential upgrade consists of the retrofit of the final steam attemperation system and the associated revised unit master control. The following figure shows the effect of the cycling plant features and start-up process on the plant's start-up time.

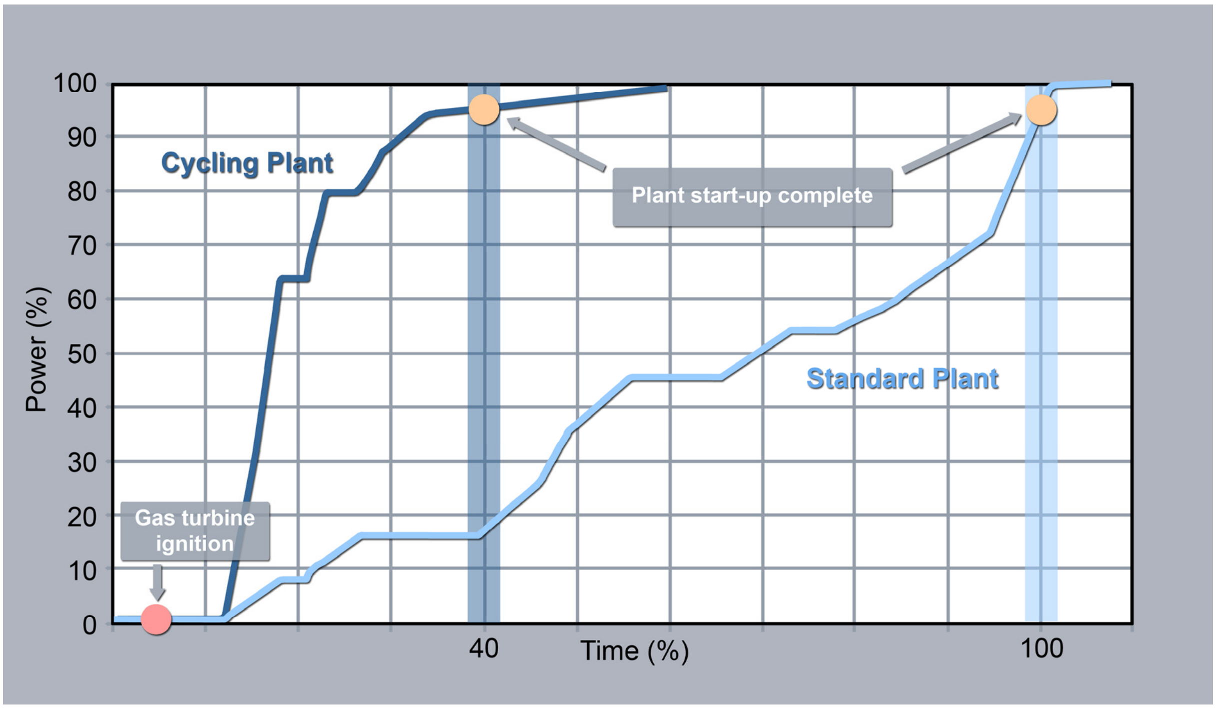

Fig. 3: Cycling plant start-up versus standard plant start-up.

3.2 Optimized Unit Start-up with Steam Turbine "Hot-start on the Fly"

A further significant improvement is based on the parallel start-up of the gas turbine and the steam turbine – the so called "hot-start on the fly". The main elements of this start-up procedure are summarized below:

- Unrestricted gas turbine start-up and loading without load hold to wait for the steam turbine start-up.
- Early steam turbine roll off with first steam production ("cold steam") at low pressure.
- Steam turbine run up to synchronized speed, synchronization and loading during continuous pressure increase.
- Lower steam production because of higher high pressure ramp rates, thus minimizing start-up losses by reduced steam dump to the condenser.
- Early closing of high pressure / intermediate pressure - bypass valves, possibly before the gas turbine is at base load or at gas turbine part load (e.g. for plant warm start).

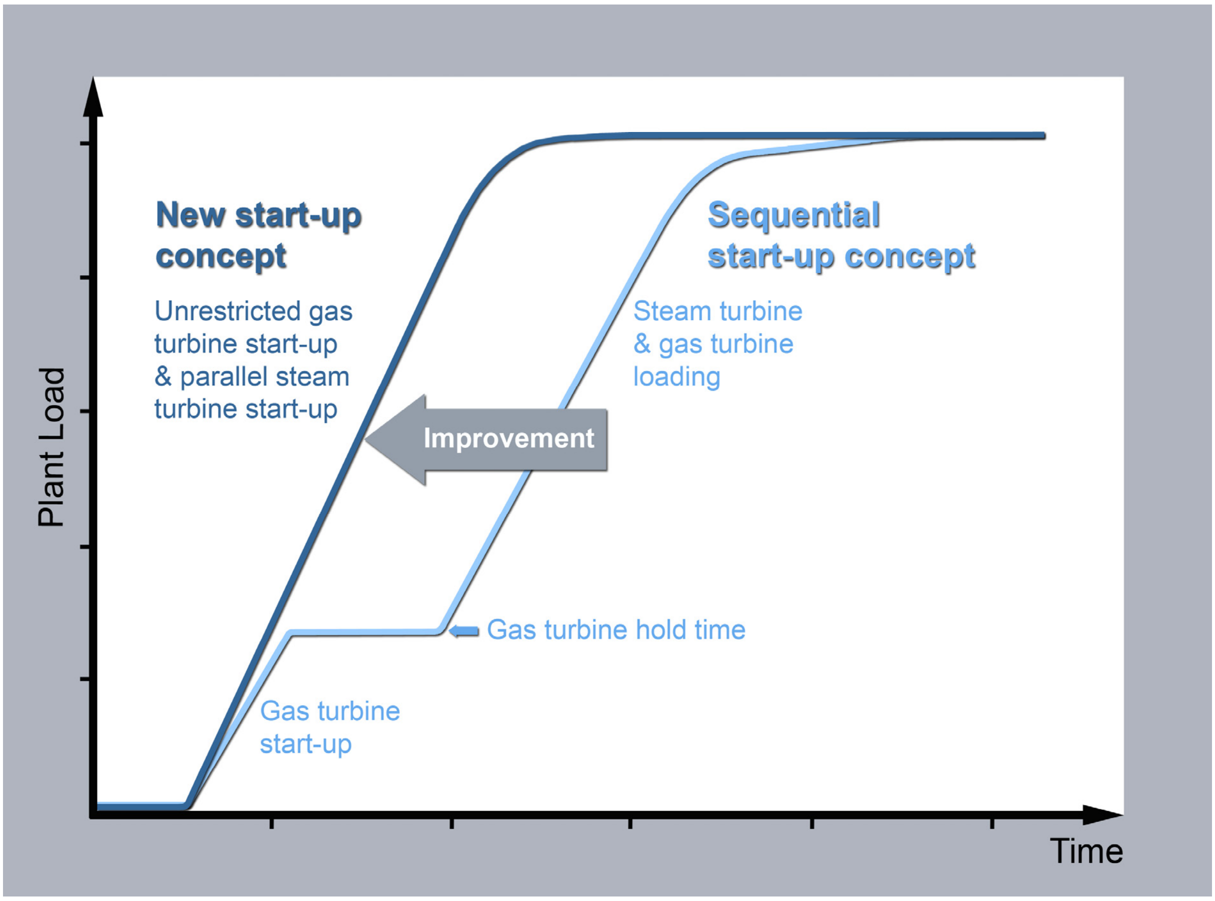

Fig. 4: New plant start-up concept with steam turbine "hot-start on the fly".

This concept includes new control concepts like a modified high pressure / hot reheat steam temperature control, a new high pressure and hot reheat bypass control philosophy, modifications in the steam turbine controller and new balance of plant system signals. An improved gas turbine control ensures usage of maximal possible load ramps over a wide operating range.

This procedure was developed, successfully tested and verified for a 400 MW single-shaft combined cycle power plant in Portugal. For a hot-restart after an overnight shut-down a total unit start-up time well below 40 minutes was achieved with a fully automated start-up procedure – from gas turbine ignition to full plant load.

4 Upgrade Opportunities

The focus of this paper is to discuss the upgrade potentials for existing combined cycle power plants. The following points are the major factors limiting the operational flexibility of existing combined cycle power plants:

- Steam turbine ramp rate restrictions
- Heat recovery steam generator pressure ramp rate restrictions
- Piping warm-up time
- Steam chemistry
- Low automation level
- Non-optimized interfaces between balance of plant, bypass controls and steam turbine controls.

A well balanced upgrade concept to improve the operational flexibility of existing combined cycle power plants must address all these limitations. Dependent on the current plant design the cycling plant upgrade may comprise lifetime evaluations of the plant components, system upgrades or retrofits and a completely revised and optimized start-up process with an associated unit controls upgrade.

4.1 Heat Recovery Steam Generator Improvements

For new units a key element to improve the operational flexibility of new power plants is the application of the once trough Benson® design steam generator, which reduces restrictions on temperature and pressure transients significantly during start-up. Since retrofitting a Benson® type high pressure section in an existing heat recovery steam generator may not be economic, the existing standard drum type steam generator can be optimized.

The first measure is to minimize heat losses out of the heat recovery steam generator-system during shut-down or active measures to keep the steam generator warm. A key element are automated drains and vents to minimize steam losses during shut-down. In order to prevent heat losses due to natural convection phenomena, two measures are recommended. The breeching between the steam generator and the stack should be insulated. A stack damper can be installed to minimize the natural convective cooling of the steam generator. In case a stack damper exists, the stack damper leakage and control can be optimized to minimize heat losses. This significantly reduces the cool down gradient of the heat recovery steam generator and provides for a faster restart.

Fig. 5: Typical heat recovery steam generator.

Another concept is to actively keep the thick walled heat recovery steam generator components like the high pressure drum warm by providing steam during shut-down. A sparging system circulates steam in the high and low pressure evaporator section(s) of the steam generator. Sparging systems could be installed on all pressure levels depending on operational parameters such as physical dimensions, design and ambient conditions. A properly designed and installed sparging system allows warm and/or hot start-ups for the same cycling characteristics which would have dictated cold and/or warm start-up rates without a sparging system. The capacity to drain superheaters and reheaters needs to be adequate to drain any residual condensate in the time allotted during the start-up cycle. The capacity is an issue of the volume of the anticipated condensate and the shut-down system. The overall drain system design needs to be coordinated to ensure that all of the components are compatible.

Additionally, the heat recovery steam generator flexibility of an existing unit can be enhanced by determining the existing component life fraction and then optimizing the stress limits of the components. The first step is to carry out a lifetime evaluation of the critical thick walled components based on existing operating data. This will “baseline” the unit critical components. The remaining lifetime is based on this calculated life and future operational scenarios. Using this methodology, a re-assessment of stress limits is possible.

Furthermore, a heat recovery steam generator stress and fatigue monitoring system can be retrofitted to the plant’s digital control system which provides an online calculation of the life consumption inside the thick walled steam generator components and a permanent information about the residual lifetime.

4.2 Steam Turbine Improvements

Looking at potentials for start-up time reduction, improvements of the steam turbine operation are fundamental. To address these limitations a steam turbine flexibility package has been developed. The first step – like for the steam generator components – is to carry out a lifetime assessment of the critical thick walled components based on operating data to evaluate the remaining lifetime. Based on the future operational scenario an optimization of stress limits is possible.

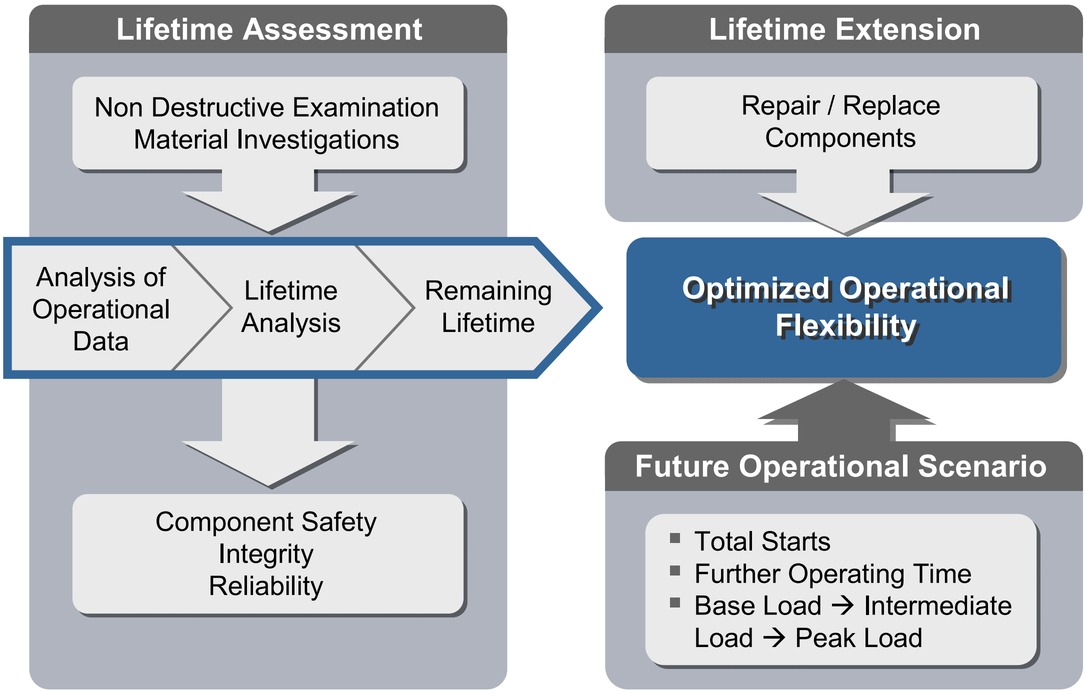

Fig. 6: Lifetime assessments as prerequisite to improve operational flexibility.

The automatic start-up sequencer and all start-up permissive will be completely revised based on the latest, proven developments. This helps to avoid unnecessary hold times or turbine trips during start-up and shut-down and thus reduces start-up time and enhances start-up reliability. New features will be implemented in the start-up sequencer like the restart capability from heat soak speed. Currently, after turbine trip, the steam turbine needs to coast down to turning gear speed before the unit can be re-started. The new feature automatically restarts the steam turbine at heat soak speed and with this reduces waiting times by up to 40 minutes.

In order to provide further flexibility, the authors' company's patented Turbine Stress Controller can be supplied. The Turbine Stress Controller consists of a stress evaluation system based on a steam turbine start-up program with an online life cycle counter. It calculates the stresses in all critical steam turbine "thick wall" components (including the valves, high pressure casing and rotor body and the intermediate pressure rotor body) depending on three different ramp rates, i.e. economic (slow), normal and fast.

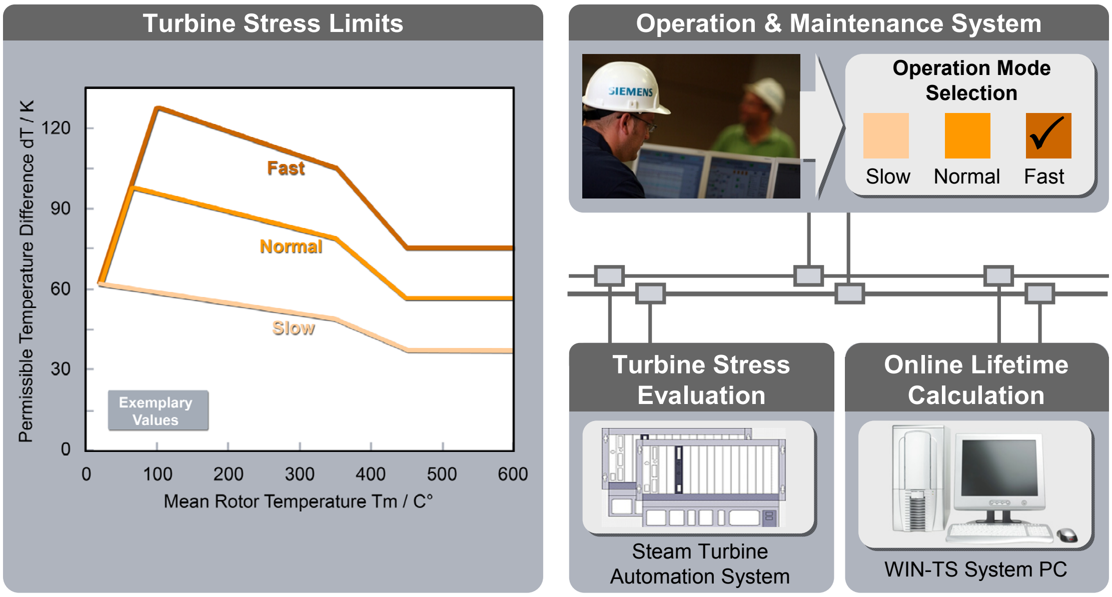

Fig. 7: Turbine Stress Controller.

The function of the Turbine Stress Controller is to control the start-up ramp rates so as to minimize material fatigue within the constraints of operating requirements and at the same time to calculate the cumulative fatigue of the monitored turbine parts. The Turbine Stress Controller assigns an appropriate number of equivalent starts for each start type - economic, normal or fast. Knowing the effects of the different start types on the maintenance schedule of the steam turbine, the owner can make prudent business decisions regarding whether or not the asset should be used to satisfy transient dispatch requirements.

Major improvements of the steam turbine and with this a shorter unit start-up time can be achieved by applying a new start-up concept in coordination with a revised unit control and the aid of final attemperators – this will be discussed in chapter 4.5.

4.3 Patented High Pressure / Hot Reheat Piping Warm-up System

The main steam entering the steam turbine has to fulfill certain requirements such as temperature, pressure and quality. After longer outages the piping has to be warmed-up to meet these requirements and in order to avoid that condensate enters the steam turbine. Furthermore, the condensate arising in the steam lines of a power plant has to be removed during the start-up to assure a safe operation of the plant.

In the past the warming of steam pipes through drain lines or additional warm-up lines has been realized. The arising condensate was collected at the low points of the pipe and removed from there. Usually, the condensate has been discharged to a flash tank. From there steam was discharged to the atmosphere and the separated water was dumped or recycled. Alternatively the steam could also be discharged to the condenser.

The high pressure / hot reheat warm-up line allows a simultaneous forward warm-up of the high pressure main steam line while the hot reheat line - downstream of the branch to the intermediate pressure bypass station - is warmed-up backwards. An automated control valve controls the flow through the warm-up line.

The installation of the high pressure / hot reheat warm-up line will shorten the time for the warming of the associated steam piping (dead legs in the high pressure and hot reheat steam piping). No water or steam will leave the water steam cycle and thus there is no additional need for make up water due to the warming process.

4.4 Steam Chemistry

As a further enhancement to rapidly achieve proper steam quality and to support rapid start-up, the cycle incorporates a condensate polisher. The polisher provides high quality feedwater to the heat recovery steam generator, thus avoiding deposits in the evaporator tubes and thereby decreasing the evaporator pressure losses. The condensate is deaerated in the condenser hotwell by vacuum, while the polisher removes the ammonia, which must then be added to the polisher effluent for proper pH-adjustment.

A key element to reduce waiting times for the required steam chemistry conditions after a shutdown is the ability of a plant to maintain vacuum over night to prevent air ingress into the condenser hotwell. To achieve this, an auxiliary boiler providing steam to the steam turbine glands during standstill as well as mechanical vacuum pumps are a prerequisite – both can be retrofitted into existing combined cycle power plants.

4.5 Optimized Start-up Processes and Unit Controls

Current Siemens design combined cycle power plants in operation apply a sequential start-up procedure. The sequential plant start-up is performed in the following way: The gas turbine is accelerated, synchronized to the grid and loaded to inlet guide vane load. The exhaust gas is lead through the heat recovery steam generator (no bypass stack) whereas steam production is dumped directly to the condenser through full capacity bypass stations. At inlet guide vane load the steam turbine and steam piping are warmed-up as well as steam chemistry is adjusted to steam turbine requirements. When all preconditions are fulfilled, the steam turbine is accelerated and steam is taken over until the bypass stations are closed (operation in fix pressure mode). The gas turbine runs up to full load and the steam turbine follows with increasing steam production. At higher loads the steam turbine operates in sliding pressure mode. This start-up procedure was designed for base load units and can be updated with the latest cycling plant procedures as described in chapter 3.2.

A key element to improve the operational flexibility of a combined cycle power plant and to shorten start-up times is the use of final steam attemperation systems to adjust steam temperatures to steam turbine requirements independent from gas turbine start-up (see 3.1). The target is to keep the steam temperature constant during loading of the steam turbine. Especially for warm and cold starts the start-up time and the load output during start-up can be significantly improved. In case an existing plant already has an attemperation system implemented it might be beneficial to increase the attemperation capacity. In case no final attemperation system exists, it can be retrofitted easily into the balance of plant system.

A significant improvement can be achieved based on a parallel start-up of the gas and the steam turbine – the so called "hot-start on the fly" (see 3.2), which can be applied for existing plants as well. After synchronization to the grid, the gas turbine is loaded continuously with its maximal allowable load ramp to base load. Exhaust gas is led through the heat recovery steam generator. With the first steam produced in the steam generator, the steam turbine is accelerated and loaded. This procedure can lead to a plant start-up time well below 40 minutes.

This concept includes new control concepts like a modified high pressure / hot reheat steam temperature control, a new high pressure and hot reheat bypass control philosophy, modifications in the steam turbine controller and new balance of plant system signals, a completely revised unit start-up sequence and an optimization of all relevant system interfaces. An improved gas turbine control ensures usage of maximal possible load ramps over a wide operating range. This upgrade is developed site-specific as an integral solution.

4.6 Enhanced Frequency Control Capabilities

In combined cycle power plants frequency control normally is provided solely by the gas turbine(s). The steam turbine is operated with fully opened control valves. In this natural sliding pressure mode the steam turbine is taking over the complete amount of steam produced in the heat recovery steam generators for maximum efficiency of the plant. Due to the steam generator's inertia changes in the gas turbine power output will result in a delayed change of power output of the steam turbine.

To improve the possible frequency response of the power plant the steam turbine can be enabled to participate in frequency control. This is done by operating the steam turbine in modified sliding pressure mode with throttled control valves. By throttling of the steam turbine control valves a certain amount of thermal energy will be stored in the heat recovery steam generators. The corresponding additional steam can be released by fast opening of the steam turbine control valves resulting in a dynamical increase of the steam turbine power output.

The modification may allow a significant dynamical improvement in power output which either enables the power plant to fulfill higher grid code requirements or in selling more reserve power to the grid.

5 Development of Site-specific Upgrade Solutions

The applicability of the fast cycling concept for existing combined cycle power plants and the associated benefits need to be evaluated on a site-specific basis and are strongly dependent on the current plant design. The starting point for a cycling plant upgrade is an evaluation based on a site assessment:

- Carry out interviews with site management and plant operators to understand plant operation, current operational constraints and dispatch situation.

- Analyze current plant configuration, check availability of cycling plant system requirements.
- Watch start-ups, analyze operating data to gather information about current start-up performance and to reveal further improvement opportunities.
- Assessment of current control logics of main components.
- Develop new operating concept based on the future operational scenario of the power plant.
- Economic evaluation of benefits by optimizing operational flexibility.

Based on the results of the assessment a site-specific upgrade package can be developed, which may comprise:

- Evaluation of the remaining lifetime of critical components.
- Optimization of plant component limitations and the start-up process based on specific operational requirements.
- Plant specific process / controls upgrade package for fast cycling.
- Retrofit of cycling plant features, as required (e.g. final attemperators, auxiliary boiler).
- Retrofit of stress control and fatigue monitoring systems.
- Implementation, commissioning and verification.

6 Benefits and Summary

The necessary additional / modified systems for a fast start-up plant lead to a certain investment for the power plant owner. But on the other hand, fast start-up and high operating flexibility shows economic benefits like reduced start-up costs, new business opportunities like spinning reserve and an improvement in the dispatch rank. Additionally, through a fast start-up the NO_x and CO emissions are reduced and the average efficiency from a load cycle increases due to short gas turbine operation in unfavorable loads. That helps customers to comply with environmental laws. In liberalized markets, the additional investment for fast start-up capability will pay off after a short time. Currently, the economic benefit from fast start-up capability is evaluated by only a few utilities. Compared with the economic evaluation of efficiency, e.g. through fuel savings, or increased power output - resulting in higher earnings - the complete evaluation of a fast start-up is more complex. Three main influencing factors for the fast start-up evaluation could be identified as follows:

- Reduction of start-up costs through fuel savings.
- Capability for participation in ancillary services markets.
- Usage of seasonal or daily market arbitrage.

This chapter shows an approach to implement these parameters in an evaluation model.

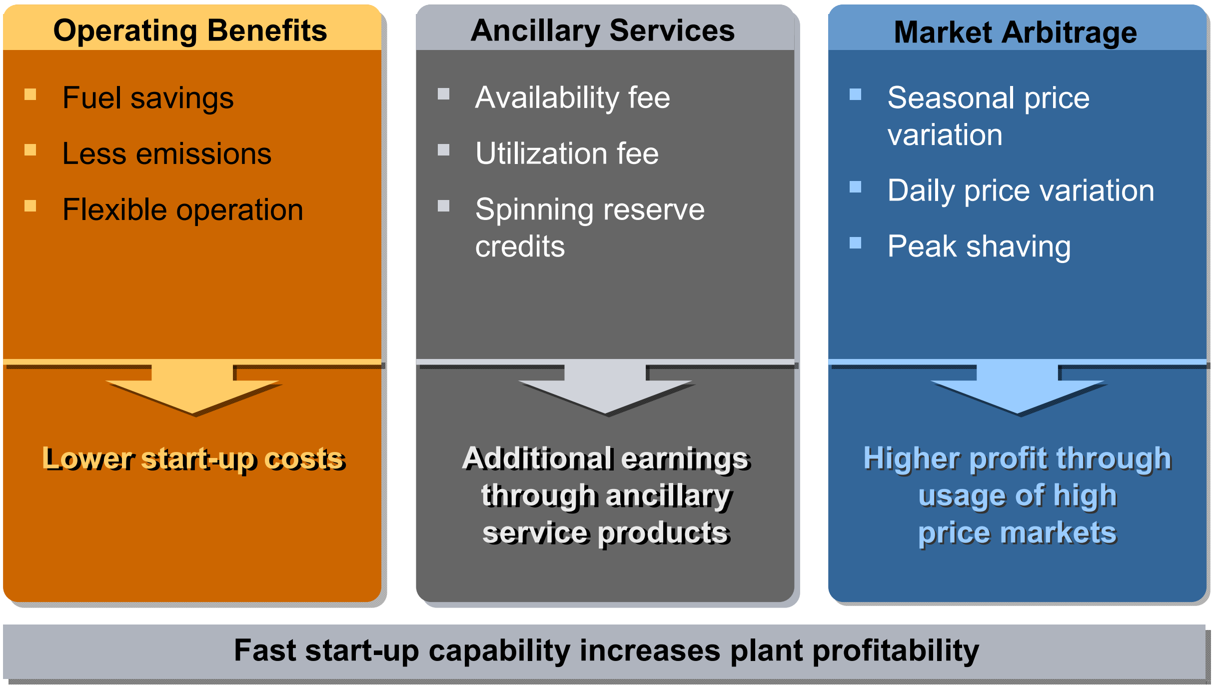

Fig. 8: Benefits of Operational Flexibility.

The actual value of enhanced operational flexibility to the customer is of course strongly dependent on the current market situation and the market mechanisms under which the power plant is operating and needs to be evaluated site-specific.

In general, high operational flexibility – the ability of a power plant for fast start-up and to adjust load output fast and predictable to changing market requirements – is an essential prerequisite to ensure economic success in a liberalized market. This paper discusses upgrade opportunities for combined cycle power plants, which were originally built and designed as a base load plant and are now - due to changing market conditions and fuel prices operated in intermediate or daily cycling mode.

Dependent on the current plant design the cycling plant upgrade may comprise lifetime evaluations of plant components, system upgrades or retrofits and a completely revised and optimized start-up process with associated unit controls upgrade. With this upgrade significant start-up time reductions can be achieved. Compared to a base load plant the start-up times can be reduced by more than 50%. A total plant hot-start after an overnight shutdown for a 400 MW unit can be performed fully automated in less than 40 minutes – from gas turbine ignition to full plant load.

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