Development of Hot Standby Mode for flexible Steam Turbine Operation

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ABSTRACT

Nowadays operational regimes of conventional power plants are more irregular and require a more flexible operation than in the past due to the increasing share of renewable energy generation. It leads to an increased number of start-ups, shutdowns and prolonged periods without dispatch. The consequences of extended standstills are longer power plant start-up times.

The new steam turbine Hot Standby Mode (HSM) concept contributes to a more flexible steam turbine operation. HSM is realized through an electrical Trace Heating System (THS). It preserves the warm start-up conditions after turbine shut-down. Herewith the start-up time can be reduced. Additionally, HSM offers many more advantages for flexible operation e.g. reduced emissions in CCPP.

At the beginning, this article will cover general aspects of flexible fossil power plant operation and point out the advantages of HSM. Afterwards the technology of the trace heating system and its application on steam turbines will be explained. Thereafter Finite-Element-Analysis (FEA) and heat transfer will be discussed. Finally the results are summarized and an outlook is given.

The aim of this work is to analyse the proposed concept and to gain a deeper insight into the heat transfer mechanisms of THS. A heat transfer correlation for flexible transient operation of the HSM was developed with a help of FEA. The HSM operation profile was optimized for a typical high-efficient steam turbine. The operation profile includes steady state, shut-down to turning gear operation, natural cooling and preserving of warm start-up conditions through heating with THS. The obtained results are encouraging.

INTRODUCTION

As renewable electrical generating capacity continues to rise, renewable power generation during advantageous weather conditions is leading to periods without any dispatch for large scale conventional power plants that last several days or even weeks. In general, the consequences of these extended shut-downs are longer power plant start-up times and moderate power ramp-up due to the low metal temperatures of the steam turbine (Eisfeld et al, 2017).

This leads to new operating profiles with higher flexibility requirements for most fossil power plants. To answer this demand, Siemens developed Flex-Power Services for a wide range of changed operational requirements (Flex-Power, 2017).

Figure 1 schematically shows the Standard Operation Line of a fossil power plant and the Flex Operation Line using the Flex-Power Services. The Flex Operation Line is characterized through increased load gradients, low load and peak power operation. These features enable a more efficient operation of the power plant with regard to performance and energy consumption during start-up, operation and shutdown. One new feature in this portfolio is HSM. It enables faster steam turbine start-up times even after long standstill times.

Figure 1 Aspects of Flex-Power Services

HSM is realized through an electrical THS which is placed on the outer casing and valves of the steam turbine. THS preserves the warm start-up conditions after turbine shut-down. The benefits are shown in figure 2 which compares start-up curves for different standstill times. Figure 2 indicates that the start-up time can be reduced by more than 60 % in HSM compared to a start-up at ambient start
conditions. Even for a standstill of 155 hours (ca. one week), as given in the example, the start-up time is almost halved.

![Figure 2 Comparison of simulated start-up curves after different standstill times](image-url)

Additionally, HSM offers further advantages for steam turbine and overall power plant operation. These are listed and explained below in detail:

- reduced lifetime consumption during start-up;
- reduced energy share that is bypassed to the condenser;
- reduced fuel costs;
- reduced emissions.

Each turbine start-up causes lifetime consumption due to the occurring temperature differences within the thick walled components. The occurring lifetime consumption can be controlled through three start-up modes which are SLOW, NORMAL and FAST. The start-up mode SLOW corresponds to the lowest and the start-up mode FAST to the highest lifetime consumption.

Cold starts are usually performed in start-up mode FAST. With the HSM the customer may chose the start-up mode NORMAL in order to achieve a reasonable start-up time with reduced lifetime consumption.

During steam turbine start-up a significant share of the energy provided by the boiler is bypassed to the condenser and is therefore lost for power production. The HSM reduces the bypassed energy share significantly because the turbine can accelerate faster from turning gear operation to nominal speed resulting in a significantly earlier initial power production. Moreover the turbine can take over the steam much faster from the bypass (compare figure 2). The additionally produced power can be sold in the market.

The HSM is beneficial for the overall start-up process of a combined cycle power plant (CCPP). In most CCPP’s the gas turbine load gradient is limited by the steam turbine during a cold start. The limitation can result from e.g. missing bypass stack or dimensioning of steam turbine bypass system. Therefore the gas turbine has to wait for the steam turbine in inlet guide vain (IGV) operation point, especially during cold starts. Gas turbine efficiency is reduced in the IGV point and thus not optimal in terms of fuel consumption. Using of the HSM reduces the fuel consumption of the GT during start-up of the CCPP.

Another aspect of the increased GT load gradient is the faster achievement of operation with minimal emissions.

Alternative concepts for hot standby operation of the steam turbine rotor are known, e.g. the use of an external steam source (Feldmüller et al, 2015) or the use of hot air (Eisfeld et al, 2017).

The focus of this work is a new concept of steam turbine HSM operation with the application of an electrical THS. HSM can be provided as a retrofit for the Siemens service fleet and combined with other modernizations. Implementing these state-of-the-art features can help power plant components remain reliable and increase the competitiveness of the plant in the changing energy market (Flex-Power, 2017).

**BASIC PRINCIPLE OF THE ELECTRICAL THS**

The basic principle of the concept is to utilize an electrical THS to supply the turbine components with heat energy. THS is installed on the outer casing surface under the insulation of a large steam turbine, usually on the HP- and IP-turbine sections of SST-3000 and SST-5000 series, see figures 3 and 4.

The electrical energy is transferred into heat through the inner resistive conductor of a mineral insulated cable, see figure 5. The mineral insulated cable is a metal sheathed cable that uses a single metallic conductor as the heating element. The conductor is electrically insulated from the metal sheath with magnesium oxide (MgO). The heat from the inner conductor is first distributed by radiation to the outer sheath and then by conduction to the outer casing. The supplied heat energy is transferred through the outer casing by conduction. The heat transfer from the outer casing to the inner casing, and further to the turbine rotor, is based on thermal radiation.

The main goal of the THS concept is to keep an equilibrium temperature state to avoid cooling down of the turbine inner parts during standstill.

The consumed power by the electrical trace heating system during standby operation is less than 0.1 % of the nominal turbine power. Using HSM several weeks of standby operation are possible without adding any additional energy because the HSM reduces the energy losses caused by bypass operation.

**INSTALLATION OF THE ELECTRICAL THS**

In this section the installation of THS on a standard high/intermediate pressure (HI) turbine is explained. A HI turbine of the SST-5000 series is shown in the figure 6, where the application surface is coloured orange. THS is mounted on the component surface under the insulation.

The electrical THS is mounted on the upper and lower outer casing as well as on the inlet valves of the HI turbine. In turbine series SST-3000 with common intermediate/low pressure (IL) turbines, the low pressure turbine section is partly heated.
Each heating zone is equipped with several heating cables in parallel providing redundancy in case a heating cable fails.

The heat conductivity between the heating cable and outer casing surface is improved through special cement as shown in figure 8. The heat flow in direction of the insulation is further reduced by covering the outer turbine casing with VA-foil, see figure 9.

For steam turbines, two types of insulation are commonly used: spray or mattress insulation. THS can be erected with either type of insulation.

The surface area is subdivided into several heat zones (not indicated on picture 6). The separate heat zones are individually temperature controlled and allow different heat flow densities at different areas. Additionally an electrical cabinet for control and power supply of the trace heating system is provided which ensures a homogeneous temperature distribution within the outer casing.

Figure 7 shows a turbine outer casing with a sub-construction carrying the mineral insulated heating cables. Each heating zone is equipped with several heating cables in parallel providing redundancy in case a heating cable fails.

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For steam turbines, two types of insulation are commonly used: spray or mattress insulation. THS can be erected with either type of insulation.

The insulation work and the installation of the THS are usually performed by qualified subcontractors with a large amount of experience.

Over the last few years, more than 150 steam turbines have been equipped with electric heating systems covering different applications. Based on the experience of both Thermoprozess (Thermoprozess, 2017) and Siemens AG, there are no apparent mechanical restrictions to prevent installation of THS on steam turbines in the fleet. Thus, retrofitting of THS is regarded as generally feasible in the context of service projects. The THS design is ensured of a lifetime to at least the next main revision.

**CONTROL OF THE ELECTRICAL THS**

Each heating zone is equipped with a temperature sensor and is individually temperature controlled through one common heating system control cabinet. It is connected to the power supply, the ST I&C cubicles and the heat zones, see figure 10. For temperature control, the heat zone surface temperature is measured. Depending on the control deviation, the power supply of the heat zone is switched on or off.

Through the signal exchange with the ST I&C cabinet, HSM is activated. Moreover, it allows the supervision of the temperature of the individual heat zone on the human-machine interface.
OPERATIONAL CONCEPT OF THE THS

The Siemens small steam (industrial) turbines of the SST-600/900 series have been using such heating systems for more than 20 years (Topel et al, 2017). Different applications for large steam turbines, e.g. the Westinghouse fleet, as well as other turbine manufacturers are also well known. However, all previous and current applications have focused on the casing’s warm-keeping mode to avoid any casing distortion during start-ups and industrial scale turbines.

In contrast to previous work (Spelling et al, 2011) this concept is focused on large scale steam turbine. If the industrial steam turbine is limited during start-up by axial and radial clearances; the large scale steam turbine is limited through lifetime consumption. Therefore the aim of the current HSM concept is just to keep a rotor of large steam turbines warm for shortened start-up times after standstills and to reduce lifetime consumption during start-up at the same time. With the electrical THS, the cool down of the turbine component is limited after 40-70h to a specific temperature. Therefore HSM is beneficial for weekends and longer time spans of turbine standstill.

In order to provide the plant owner the maximum operational flexibility, HSM can be operated with or without seal steam. HSM operation with seal steam will allow faster power plant start times because evacuation is present and there is no need to wait for steam purity release. Whereas HSM without seal steam leads to the same steam turbine start-up time but increased power plant start-up times because e.g. steam purity is not fulfilled. Otherwise, HSM without seal steam is more cost efficient because the auxiliary boiler can be switched off.

Hence, HSM operation with seal steam seems to be more cost efficient for mid standstills and HSM without seal steam for prolonged standstills. The definition of mid and prolonged standstills depends on the specific economic boundaries of the plant owner.

In the following section, deeper insight into the heat transfer mechanisms during HSM operation is investigated. Numerical simulations based on Finite Element Analysis (FEA) for different turbine series were conducted. This article will present some results of the turbine series SST-5000 which is shown in figure 6.

The numerical calculation results are encouraging. Nevertheless, it is always beneficial to validate the FE calculations in a lab or by plant tests to gain more practical experience for customers’ optimized operations. The implementation of an electrical trace heating system to improve start-up behaviour of a CCPP with an F-Class gas turbine and SST-3000 is planned in Europe in late 2017 (Eisfeld et al, 2017).

THS DIMENSIONING ON AN HI STEAM TURBINE

The following section examines the design of the THS concept by means of FEA. The objective of the analysis is to investigate the THS efficiency and gain insight into the heat transfer and temperature distribution in the turbine components over the time. The thermal analysis is a basis for the subsequent structural analysis with a focus on transient
operation and clearance assessment. As such, the feasibility and permissibility of the THS concept with and without seal steam supply for a HI turbine of SST-5000 series is evaluated.

The main mechanism of the THS concept is a heat transfer in which radiation dominates. Heat transfer by radiation differs from other forms of heat transfer, e.g. convection, because electromagnetic radiation transports the heat through the space without the need for a medium between the heat exchanging objects. Heat radiation exchange takes place as a transient process according to:

$$\dot{Q}_{rad} = f(A, f_v, \psi, \sigma, \varepsilon, \Delta T^4)$$  \hspace{1cm} (1)

whereby $\dot{Q}_{rad}$ is a heat flux by radiation, $A$ is an emitting body surface, $f_v$ is the view factor, $\psi$ is absorptivity, $\sigma$ is the Stefan-Boltzmann constant, $\varepsilon$ is an emission coefficient and $\Delta T$ a temperature difference between considered surfaces or to ambient temperature. The actual heat flux by radiation is difficult to detect due to different parameters, e.g. the emission coefficient. For this reason, estimation of the losses from the total emitted energy onto the receivers needs to be accurately validated.

The used calculation model takes also into account both heat transfer mechanisms: radiation (1) and convection (2).

The current FEA was done with the Abaqus/CAE software developed by Dassault Systèmes Simulia Corporation (ABAQUS, 2017). For this work, an axisymmetric 2D-model of an HI turbine was created. The boundary conditions that were applied to the FE model are the steam and ambient temperatures in the turbine sections and the heat transfer coefficients.

The impact from THS is modelled with the help of convective heat transfer coefficients and radiation parameters according to specific internal Siemens rules. The blue line in figure 11a shows THS boundary conditions as constant heat flux constant on the outer casing surface. Figures 11b and 11c show the definition of the interaction between emitting and absorbing surfaces inside of the turbine, marked with red lines. As such, the interaction is realized both between the inner surface of the outer casing and the outer surface of the inner casing (figure 11b) as well as between the inner surface of the inner casing and the rotor (figure 11c).

In the current study, the convective heat transfer coefficients as well as the steam or ambient temperatures were applied as time-dependent variables. The variables were verified by means of the measurement data. The boundary conditions were adjusted in such a way that the simulated natural cooling down curves corresponded to the measured temperature records. One example of such temperature measurement on an HI turbine of the SST-5000 series is given in the figure 12 for the HP/IP inlet rotor and the HP/IP inlet inner casing as well as for the outer casing areas. The seal steam temperature is set to be under operational conditions at time point a/b (shut-down to turning gear operation) and is off at time point c. The temperature distribution is normalized with the maximal operation temperature of the turbine. The time scale is weighted by the amount of time a specific rotor temperature will be achieved.

The radiation was defined as open cavity radiation, whereby the intensity of radiation is managed by calculated view factors between defined emitting and absorbing surfaces. The chosen method of radiation definition shows good correlation evidence for such kind of heat transfer, confirmed by field tests.
Figure 13 shows a sketch of one of the investigated loading profiles: cooling phase during standstill and following THS operation. The idealized temperature profile corresponds to an example of cooling down and following HSM. The temperature decreases after shutdown from its operation maximum at time 0 until HSM is demanded.

Three measuring points in the Inner Casing (IC) and two measuring points in the Outer Casing (OC), as shown in figure 14, were considered for the model adjustment: 1) HP exhaust steam temperature; 2) HP inner casing temperature; 3) IP casing temperature; 4) IP exhaust steam temperature; 5) OC inner casing temperature.

The starting point for validation of the measured cooling down curves was a nominal steady-state load case. The boundary conditions were determined according to the thermo-dynamic cross-section and by applying current design rules. The model is able to replicate the measured temperatures with a high level of accuracy (compare figures 12 and 15). For further validation of the FE model, the load case natural cooling with seal steam was calculated. It can be assumed that the model is able to deliver reasonable results for the HSM load case according to THS concept after shutdown and subsequent standstill of e.g. 40-70 hours. The results of FEA are temperature distribution and heat flux history of the turbine components under THS loading during a hold time.

The obtained temperature field is applied for the subsequent structural analysis. The results of the structural analysis are primarily used to verify the clearances and secondarily for estimation of lifetime consumption.

Figure 15 shows normalized temperature behaviour according to the loading profile given in figure 13 in the HP/IP inlet section at the rotor and the inner casing as well as in the outer casing.
temperatures in the inlet areas are simulated to be approx. 0.45 of the operational temperature (point a) for both the HP- and IP-rotors. This is a criterion for the quick start-up after standstill. Figures 16d and 16e show the temperature distribution at time point d and e (figure 15). That is the transition time frame when the maximal allowable cooling of the rotor is reached. During this period THS should be switched on to ensure a thermally balanced state of the inner components. It is apparent that, with the THS concept, the local and integral rotor temperatures can be maintained at between approx. 0.4 and 0.5 of the operational temperature for quick start-up after a standstill time (figures 16e, 16f, 16g and 16h). After demand of HSM at point e (figures 15) one can observe that the rotor temperature can be kept (point g) and even slightly increased until thermally balanced state of components will be reached at point h.

The FE results seem to be plausible. FEA indicates that an integral rotor temperature can be achieved which is approx. 25% below the outer casing temperature when equipped with THS. It is advantageous to verify the boundary conditions - during the commercial application - by means of an elaborate measurement set-up.

Figures 16 Temperature distribution during cooling and following THS operation, calculated

Mechanical analysis focusing on the clearance assessment was carried out. The analysis revealed that the THS concept is feasible for the HI-turbine as well as for the other large turbines e.g. HP, IL. For large steam turbines, the axial and radial expansions are covered by the implemented clearance design. Furthermore, close monitoring of the turning speed as well as monitoring of the casing temperature differences (top/bottom) is advisable. With these measures, safe operation of the turbine can be ensured.

FEA results are also used for the dimensioning of THS. The needed energy flux was calculated to determine the density of THS over the outer casing (OC) surface. For this purpose two energy balance calculations are done. The first calculation is done for the time period from the point e till point h (figure 15) until a thermally balanced state of permanent THS supply is reached. The second one is needed for estimation of needed energy after the saturation point h (figure 15) to compensate the losses. A small amount of energy is lost to the surroundings through the insulation, but can be ignored. The energy loss which occurs in the rotor bearing area is more significant and can be calculated as shown in figure 17. It is obvious that at time point h the most loss occurs in the rotor bearing area with a maximum temperature gradient, figure 17a. This loss can be analysed at each time point in the form of heat flux in Watt per unit area (ABAQUS, 2017) as shown in the Figure 17b for time point h.

The balance compilation of the total radiation heat flux \(Q_{\text{tot THS}}\) of components provides information about energy demand and losses for proper dimensioning of THS as given in (3) and in the figure 18a as example of THS heat flux by radiation leaving OC and incident on receivers (IC & rotor) at time point e, as defined in figure 15.

\[
\dot{Q}_{\text{tot THS}} = \dot{Q}_{\text{Receivers}} + \dot{Q}_{\text{Loss}},
\]

whereby \(\dot{Q}_{\text{tot THS}}\) is total radiation heat flux emitted by THS and \(\dot{Q}_{\text{Receivers}}\) as well as \(\dot{Q}_{\text{Loss}}\) are correspondingly absorbed heat flux by receivers (IC and rotor) and losses. As shown in the figure 18b the IC is main receiver at time point e.

Finally, based on this information, the THS density including safety factor and the number of needed heat zones for turbine outer surface - as described in the previous paragraph (see figure 6) - can be defined.

\[
D_{\text{THS}} = f \cdot \frac{\dot{Q}_{\text{tot THS}}}{\sum A_i}, \quad \dot{Q}_{\text{tot THS}} \geq \dot{Q}_{\text{Loss}},
\]

whereby \(D_{\text{THS}}\) is a density of THS, \(f\) is safety factor, \(\dot{Q}_{\text{tot THS}}\) is radiation power or total radiation heat flux energy and \(A_i\) are designed surfaces of heat zones of the steam turbine outer casing. In this way the number of heat zones dependent on the turbine topology and customer’s requirements are defined.

Figure 17 Temperature and corresponding heat flux distribution at time point h
SUMMARY AND OUTLOOK

The Steam Turbine Hot Standby Mode preserves the warm start conditions for a standstill time greater than 40-70 hours. The resulting steam turbine start-up time is significantly reduced, i.e. by more than 60% compared to a cold start from ambient conditions. This enables fast start-up times – even after long standstill times – if attractive market conditions occur. The flexible operational concept allows the customer to preserve the steam turbine warm start conditions either with or without seal steam depending on their own commercial targets. In future developments, two aspects will be pursued. The first aspect is to increase the standby temperature. Thereby the steam turbine start-up time can be reduced even further. The second aspect is to heat up a turbine from ambient conditions. As a result the energy consumption for long standstill times can be minimized because THS can be switched off.

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NOMENCLATURE

- **A**: Surface
- **CCPP**: Combined Cycle Power Plant
- **D_{THS}**: Density of THS
- **ESH**: Equivalent Start-up Hours
- **f**: Safety Factor
- **f_Y**: View Factor
- **FEA**: Finite Element Analysis
- **H/-I/-L**: High/Intermediate/Low Pressure
- **HSM**: Hot Standby Mode
- **IC/OC**: Inner Casing/Outer Casing
- **Q**: Heat Flux
- **ST**: Steam Turbine
- **T**: Temperature
- **THS**: Trace Heating System
- **α**: Heat Transfer Coefficient
- **ε**: Emission Coefficient
- **σ**: Stefan-Boltzmann Constant
- **ψ**: Absorptivity

REFERENCES


