Proceedings of GPPS Forum 18
Global Power and Propulsion Society
Zurich, 10th-12th January 2018
www.gpps.global

GPPF-2018-23

Modelling of Angle Controlled Engagement for a Single Shaft CCPP with Mechanically Decoupled LP Turbine for Maximum Heat Extraction

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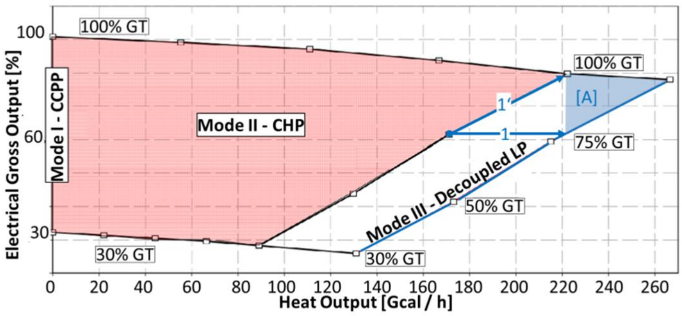
ABSTRACT

A new configuration for a single shaft gas and steam turbine with an extraction for district heating in the cross over pipe was developed. It allows maximum heat extraction and operational flexibility by entirely shutting off the low pressure turbine (LP), thermodynamically by a steam tight valve and mechanically by a semi-rigid clutch.

Clutch engagement control (CEC) for single shaft CCPP applications is proven to positively affect the rotordynamic behaviour in single shaft trains with one SSS-clutch between generator and steam turbine. The new train has an additional clutch between IP- and LP turbine. CEC will be used to reconnect the LP at nominal speed but also at low speed using the electrical turn motor. This is far more challenging due to the low sampling rates and the limited acceleration rate of the electrical drive. The requirements to enable CEC for this application were intensely analysed with tailored Matlab/Simulink models for dynamic simulation of the engagement process.

INTRODUCTION

One approach to solve the energy trilemma of providing security of supply at low cost and minimum environmental impact could be the application of flexible operating steam turbines with district heating [1]. Obviously these are particularly worthwhile in areas with low ambient temperatures and high heating demands [2]. These combined heat and power plants (CHP) have a wide operating regime, with daily and seasonal load cycles (e.g. summer vs. winter / day time vs. night time). Typical operation modes are shown in Figure 1. Mode I shows the cycling capacity of a standard combined power plant (CCPP). This is limited at the top by the maximum output of the gas turbine (GT) and at the bottom by the boiler. The area of Mode II shows the typical operating regime of a CHP plant. Maximum heat extraction at the right hand side is limited by windage of the LP turbine. If further mass flow is extracted to the district heating system the LP turbine will start to heat up. This restricts the thermal power that could otherwise be extracted [Line 1]. Hence excess electrical output needs to be generated to cover the thermal demand [Line 1']. With the capability to decouple the LP turbine this can be prevented to some extent. It can be seen that by decoupling the LP turbine (Mode III) the maximum heat output can be increased beyond the amount that is possible by traditional heat extraction [A]. Additionally the range where flexible operation is possible is extended.



Mode	Descriptions	Remarks
I	HP/IP+LP operation	Standard CCPP. Full condensing. No District Heating.
II	Electricity priority operation	Partially condensing
III	LP turbine disengaged; turn drive in operation; all steam produced in the HRSGs is fed into the district heating.	Decoupled LP. Maximum heat extraction.

Figure 1 Typical operation modes of a CHP

A mechanically decoupled LP has the advantage that the highest amount of heat can be extracted. This occurs at a high efficiency as there are no adverse effects like windage losses or the necessity to use steam for cooling the last stage blades. By using an overrunning clutch to mechanically connect and disconnect the LP turbine the configuration achieves a high availability and operational flexibility nearly comparable to that of a thermally decoupled approach.

In general one or more extractions to the heating system are possible. The amount of extractions in the steam turbine depends on the priorities of the customer. While increasing the number of extractions increases overall efficiency of the power plant, it also increases cost and complexity [3]. A configuration as shown in Figure 2 with one extraction placed in the cross over pipe of the steam turbine has the benefit that the standard CCPP plant layout concept with low level arrangement of the steam turbine can be maintained. A butterfly valve combination in the cross over pipe handles the flexible operation by maintaining a constant pressure level. An overrunning clutch between the LP turbine and the combined high and intermediate pressure turbine (HP/IP) handles fast on/off operation of the LP and hence ensures maximum capacity of heat extraction. In a single-shaft arrangement only one generator is required which is shared by gas and steam turbine.

This configuration is perfect in terms of fast response to changing demands at very low cost.

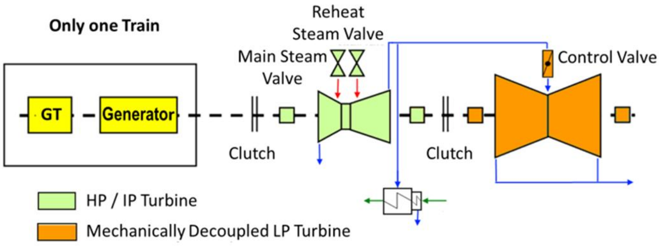


Figure 2 Single-shaft CHP turbine train configuration with one extraction

GENERAL DESCRIPTION OF CONFIGURATION

The configuration is shown in more detail in Figure 3. The configuration is a single-shaft application with one generator being shared by the steam and gas turbine. The generator is rigidly connected to the gas turbine. The HP/IP section of the steam turbine can be engaged with the generator by an overrunning synchro-self-shifting clutch (SSS1). The LP turbine can be kept engaged to the HP/IP section of the turbine by a semi-rigid SSS clutch (SSS2) which can be locked close by means of a switch. At the other end of the low pressure turbine a turn drive (TD) can be connected by another semi-rigid clutch. There is a speed sensor on each separate section of the train. The valve combination in the cross over pipe must handle start-up and shut-down processes as well as load changes. Hence the valve combination consists of a steam tight shut-off butterfly valve (LP SV), a large control butterfly valve (LP CV) and a small LP start up valve (LP SUV). This configuration has the advantage that it is possible to engage and disengage the LP turbine without shutting down the HP/IP turbine to zero speed. This is a huge time advantage in terms of availability and flexibility.

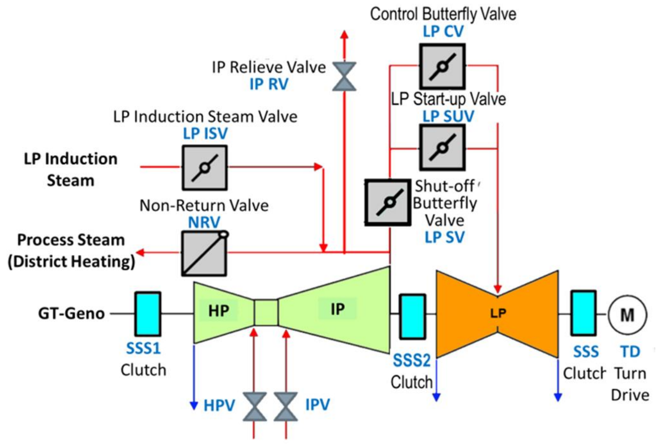


Figure 3 Configuration detail

Due to the construction of the SSS clutch two shafts can only engage at discrete positions, evenly spaced around the full circle. These positions can be distinguished through the angel between the two shafts with respect to an arbitrarily chosen angle which is defined as zero.

It was observed at some single shaft power plants that there are favourable and unfavourable regions for the engagement angle with respect to shaft vibrations. Figure 4 provides an example.

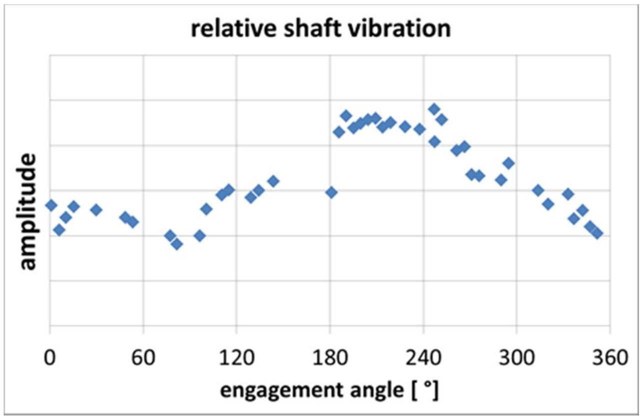


Figure 4 Relative shaft vibration for different engagement angles

The same behaviour is expected for the engagement between IP turbine and LP turbine. Consequently, a reproducible engagement angle enables the operator to positively affect the vibrational behaviour of a single shaft CCPP.

OPERATING POINTS AND MODELLING CASES

For disengaging the LP turbine the locking switch of SSS2 is opened and the valve combination is closed. To prevent the LP from running at an unfavourable idle speed, for example in an exclusion zone, a steam tight valve combination is used. Additionally the turn drive has the capability to act as a break.

During operation Mode I and II the LP turbine is connected to the HP/IP turbine (SSS2 engaged and locked). LP SV is always open and LP SUV is always closed. Load changes are performed with LP CV. LP CV can be closed up to a minimum mass flow. After that LP CV and LP SV are closed and LP turbine is running down. If necessary the turning gear engages at idling speed and ensures LP turning speed is achieved.

Two scenarios to reconnect the LP turbine exist:

Case 1: Engagement at full speed: GT & HP/IP remain in operation, LP start-up

Case 2: Engagement at HP/IP run-down

In each scenario the engagement angle between the rotor sections should occur at an angle that results into the least vibrations for the overall shaft.

In scenario 1 the HP/IP turbine is connected to the GT-generator operating at nominal speed. The LP turbine is at turning speed. LP SV and LP CV are closed. LP SUV is slightly opened to prevent accumulation of water in the cross over pipe. Start-up of the LP is initiated by opening the LP SV. Speed controlled start-up and controlled engagement is handled by the LP SUV.

In scenario 2 the HP/IP turbine is running down. As a restart of the HP/IP turbine without the LP turbine is not permissible SSS2 must be engaged before restarting the steam turbine. The LP turbine is at turning speed and the lock of the semi-rigid clutch of the turn drive is locked. At a certain idling speed of the HP/IP turbine the turning gear starts to accelerate the LP turbine. Controlled engagement is handled by the turn drive. The steam turbine can now go into turning mode or re-start.

CONTROL OBJECTIVE AND CONTROL STRATEGY

In order to force the engagement to occur at the most desirable angle, a control algorithm was developed. The controller adjusts the acceleration of the steam turbine such that the engagement takes place at a predefined angle. The respective controller was already successfully implemented at several single shaft CCPPs (see [6]). The same principle shall be used to engage the LP turbine at a previously determined favourable angle. In the context of the engagement of the LP turbine, the concept has been simulated but not jet tested on site.

In contrast to the situation at single shaft CCPPs the LP section not only has to be engaged at nominal speed but also at low frequencies. It was found that the latter task results into additional challenges concerning the required sampling times.

The requirements for angle controlled engagement of the LP turbine at nominal speed as well as at turning gear are analysed. In case 1 the HP/IP turbine is at nominal speed and the LP turbine is accelerated with steam. The required control is conducted with the LP-butterfly control valve (LP CV). In case 2 the HP/IP turbine is slightly above turning speed. The acceleration of the LP turbine is realized by an electrical turning gear

The principle of the algorithm for angle controlled clutch engagement can be summarized by the following considerations:

At a chosen speed difference of $1\mathrm{Hz}$ between HP/IP- and LP-shaft the LP turbine shall be accelerated with different gradients. Depending on the chosen gradient, the time till engagement as well as the resulting engagement angle between the two shafts varies.

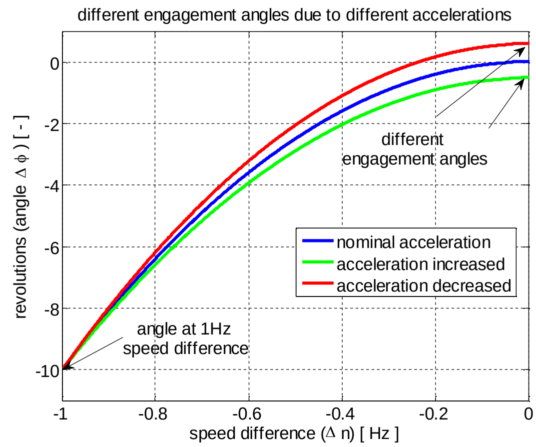


Figure 5 Dependency of clutch engagement angle on chosen acceleration

Figure 5 reveals that a small acceleration yields a large angle and vice versa. Conversely, if a certain engagement angle is aimed at, this goal can be obtained by choosing the 'right' acceleration. The overall control strategy which integrates the above considerations for engagement at a desired angle is the following:

The LP turbine is accelerated with a given gradient until it's speed is slightly below the speed of the HP/IP turbine. At this point the acceleration of the steam turbine is reduced. Here a reduced acceleration of $0.05\mathrm{Hz/s}$ is chosen.

As soon as the LP turbine speed is $1\mathrm{Hz}$ below the speed of the HP/IP turbine, the clutch angle controller takes over and determines the set-point trajectory for the LP-speed, n_{LP}, or the difference between the desired and actual LP turbine speed, $\Delta n_{LP} = n_{LP,s} - n_{LP}$, respectively. The controller switches from ramp-up modus to the controlled engagement modus.

Ramp-up of the LP turbine is conducted by speed control with the turbine governor only.

Figure 6 outlines the proposed control concept.

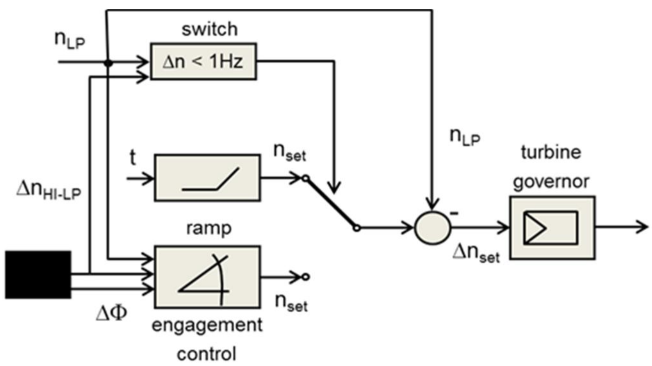


Figure 6 Engagement angle control concept

Details of the clutch engagement control algorithm are outlined in [6].

SIMULATION MODEL

In order to analyse the feasibility as well as the requirements for the proposed control, a simulation model was set up in MATLAB/SIMULINK to investigate the engagement of the decoupled LP turbine to the remaining shaft under a predefined angle. The Simulation model contains:

- a thermodynamic model of the LP-turbine turbine
- a mechanical model of the LP turbine shaft
- a simplified model of the LP start-up butterfly valve including the actuator
- the electrical turning gear
- a simplified model of the SSS-clutch between LP and HP/IP turbine
- a reduced model the existing I&C logic
- the required measurements
- the clutch engagement controller

The remaining part of the turbine, i.e. the HP/IP turbine, is represented by a given speed only. In the following the simulation models are outlined.

LP Turbine

The LP turbine is modelled by a simplified description of the turbine thermodynamics.

The pressure as well as the enthalpy in front of the start-up butterfly valve is assumed to be constant. The butterfly valve is modelled by a throttle equation that accounts for the diameter of the valve as well as for its respective angle. Swallowing capacity and power output along the blading path is modelled according to Stodola's law. Losses due to windage are considered.

In front of the blading the pressure builds up depending on the pressure in front of the butterfly valve and its admission area. Constant condenser pressure is assumed downstream the blading path.

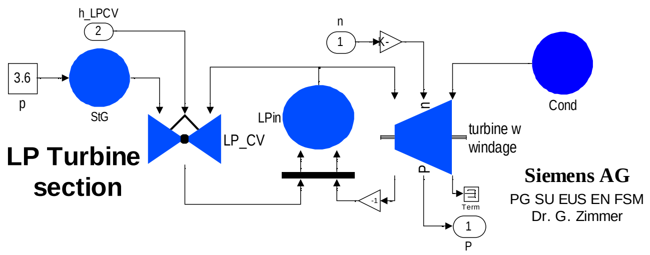


Figure 7 Thermodynamic model of the LP turbine

LP Turbine Shaft

The LP turbine shaft model simulates the change of speed due to increasing and braking of the angular momentum Shaft inertia as well as nominal speed is considered.

LP Start-up Butterfly Valve Including the Actuator

The actuator of the LP SUV considers the flap angle and angle set-point, controller gain, velocity limitations and I&C delay. The non-linear relation between angle and admission area is accounted for by an S-curve which is based on the measured kv-values.

Electrical Turning Gear

During coast down of the disengaged HP/IP turbine, reengagement of the LP turbine is conducted with an electrically operated turning gear. This motor is depicted as a PT1 element with a delay of 0.5s which is limited by the maximum motor torque.

SSS-Clutch

The internal model of the SSS-clutch simulates the change in the angle of the sliding component while engaging or disengaging. The engagement process of the sliding component of the SSS-clutch takes place over an angle of 20°. This value is due to the construction of the SSS-clutch. Any disengaged operation returns the angle 0 for the sliding component. The operating principle of the SSS-clutch is thoroughly described in [4].

Torques and damping due to oil friction is considered. A full order model of the SSS-clutch is described in [5].

I&C Logic and Speed Load Control

The time delays from the existing I&C logic are depicted.

Acceleration of the decoupled LP turbine is conducted with a speed-admission logic that was set-up similar to the logic implemented in the turbine governor for turbine speed and load control. The speed control is conducted by a PI-control.

Required Sampling of Measurements

Clutch angle control requires the HP/IP turbine speed, the speed difference between HP/IP- and LP turbine, as well as the measured angle as inputs. The angle between HP/IP turbine and LP turbine has to be measured with a small sampling time to achieve sufficient precision. Using one mark per revolution, a sampling time of 20 ms can be achieved near nominal speed without further effort. This sampling time is sufficient if the LP section is engaged to the HP/IP turbine at nominal speed. The sampling time is reciprocal to the speed. Thus the resulting sampling time is significantly larger in the vicinity of turning speed. This issue is addressed later on.

Clutch Angle Engagement Controller

Analogously to [6], the measured value of Δn_{LP}, delivered by the measurement transducer, and the measurement of n_{LP} is used. The signal Δn_{LP} is additionally used for the subsequent switch which decides whether ramp-up modus or controlled engagement modus is active.

Depending on the respective rotational speeds and relation between the measured angle and the desired engagement angle, the controller calculates a LP turbine speed set-point. In order to cope with disturbed steam turbine speed - or shaft speeds, respectively - e.g. oscillations or ramps in the electrical grid, the LP turbine speed set-point is determined relative to the measured turbine speed.

More details on modelling of the respective components are given in [6].

Overall Model

The overall simulation model is depicted in Figure 8. Additional to the sub-models mentioned above, the overall simulation model requires a (simulated) shaft speed of the HP/IP turbine as well as a ramp-up strategy.

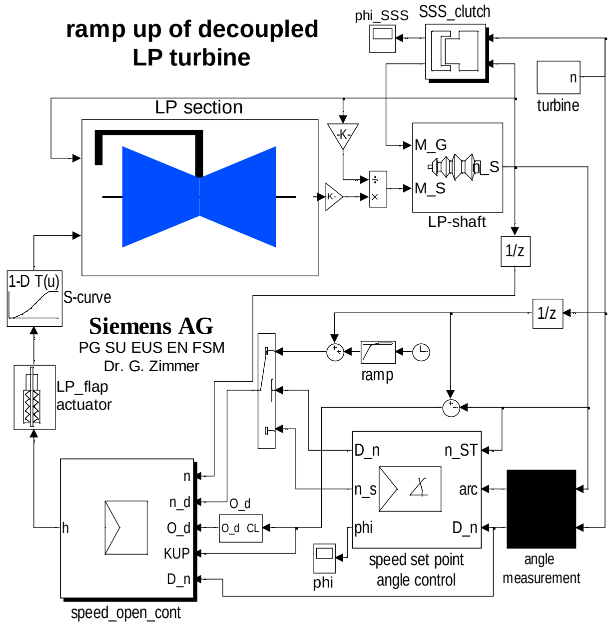


Figure 8 Overall simulation model (LP and HP/IP section engaged at nominal speed)

Please note that the above model describes case 1 where the LP turbine is engaged to the HP/IP turbine at nominal speed, so that the HP/IP turbine is not modelled. In case 2 the LP turbine is re-engaged with the turning gear, thus the thermodynamic details of the LP turbine are not required. Consequently, in case 2 the LP turbine block is substituted by the simpler model of the turning gear.

SIMULATION RESULTS

Several simulations were conducted to investigate the feasibility of the concept, to determine susceptibility towards boundary conditions and to determine the size of the required components.

The analysis distinguishes between controlled engagement at nominal speed (case 1) and at turning speed (case 2). Case 1 is operated with the LP start up butterfly valve. Case 2 is operated with the turning gear.

Engagement at Nominal Speed (Case 1)

Feasibility

Firstly, feasibility of the outlined concept is investigated. The respective boundary conditions are as follows:

- The disengaged LP turbine is ramped-up from turning speed
- The pressure in front of the butterfly control valve is fixed
- The sampling times are arbitrarily small, i.e. almost 0.

Ramp-up is performed with a standard gradient until the speed difference between HP/IP turbine and LP turbine is 1Hz. At this point the control switches from nominal ramp-up mode to clutch-engagement mode.

Figure 9 gives an example of the incorporated dynamics.

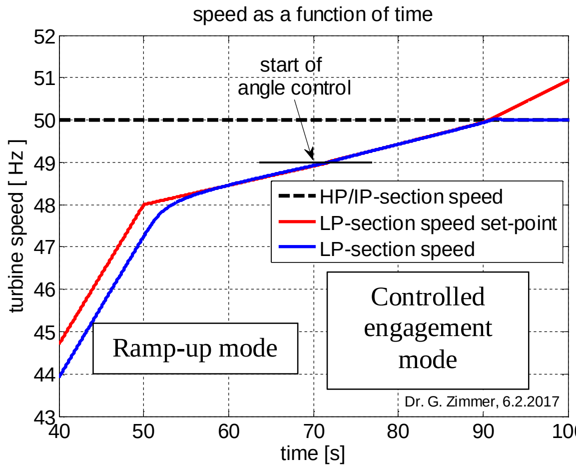


Figure 9 Speed set-point and actual speed (simulation) for the LP turbine at ramp-up

For the chosen configuration, the engagement occurs while the LP SUV was not completely opened, thus allowing for some margin.

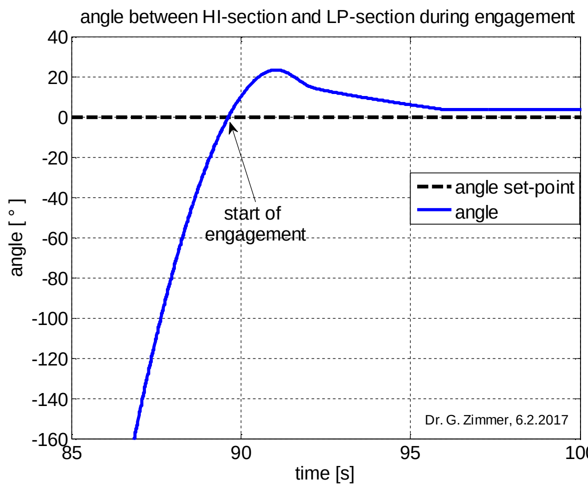


Figure 10 Angle between HP/IP- and LP section prior to engagement; set-point is 0°

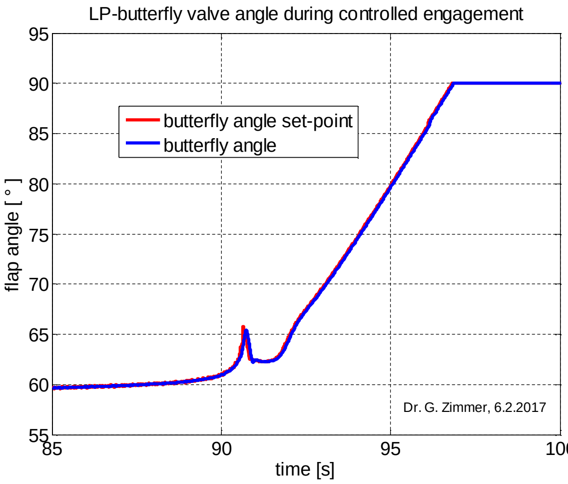


Figure 11 Angle of LP butterfly control valve prior to engagement; possible maximum is 90°

Figures 10 and 11 show a peak in the acceleration - shown by the peak in the LP SUV angle - when the engagement starts. This is due to the increased braking torque of the SSS-clutch once the engagement is initiated. Figure 9 additionally shows that the deviation between the desired engagement angle and the achieved engagement angle is less than 5°. Due to the construction of the SSS-clutch engagement can only occur at discrete positions which are approximately 5° apart from each other. This is due to the distance between two teeth of the SSS-clutch which realize the final engagement position. Consequently, the accuracy cannot be further improved.

The above depicted simulations confirm the theoretical feasibility of the outlined concept.

Determination of Boundaries

In the second step the boundaries for the application are evaluated. To this end, several parameters and boundary conditions are combined to determine the most sensitive influence parameters as well as the required properties of the incorporated components.

It is shown in table 1 and 2 that the ramp-up is sensitive towards the combination of steam pressure and valve size. Neither the standard sampling times nor the standard travel times of the LP SUV cause any issues.

pressure \ travel time	2s	4s	6s	8s	10s	12s
3 bar	-	-	-	-	-	-
3.5 bar	✓	✓	✓	✓	✓	(✓)
4 bar	✓	✓	✓	✓	✓	(✓)
5 bar	✓	✓	✓	✓	✓	✓

Table 1 Investigation of successful engagement with DN 250 butterfly valve

pressure \ travel time	2s	4s	6s	8s	10s	12s
3 bar	✓	✓	✓	✓	✓	✓
4 bar	✓	✓	✓	✓	✓	✓
5 bar	✓	✓	✓	✓	✓	✓

Table 2 Investigation of successful engagement with DN 350 butterfly valve

According to Tables 1 and 2 a small valve is sufficient if the pressure in front of the valve is high enough. In this case the pressure must be at least 3 bars. If a pressure of more than 3 bars can't be guaranteed, a larger valve is required.

Engagement at Drag Speed (Case 2)

Before the engagement at drag speed is investigated, the drag speed of the HP/IP and LP turbines themselves are determined (Figure 12).

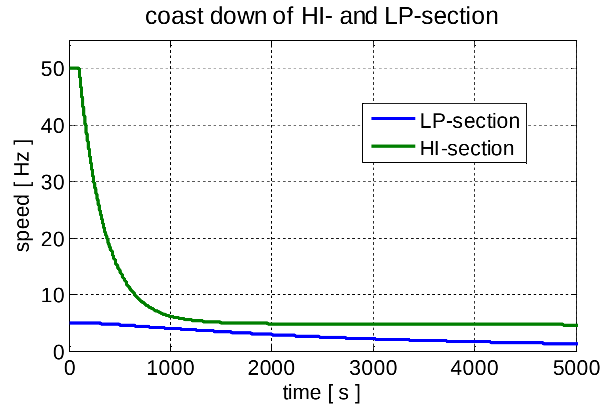


Figure 12 Drag speed of LP- and HP/IP turbine

Figure 12 shows that the drag speed of the LP turbine is at around 6 Hz while the HP/IP turbine is at nominal speed. If the HP/IP turbine coasts down, the drag speed of the LP turbine decreases. As long as the gas turbine is at nominal speed the HP/IP turbine remains at approximately 6 Hz. Without further action the LP turbine coasts down to approximately 1Hz.

In order to increase operational flexibility, the LP turbine shall be able to engage to the HP/IP turbine while it is coasting down as well as from a start position where both steam turbine sections are disengaged and at their respective drag speeds. This removes the necessity to shut down the entire plant in order to mechanically engage HP/IP- and LP turbine before restarting the steam turbine.

Simulation results revealed that the standard sampling of one signal update per revolution for speed and angular difference between HP/IP- and LP turbine is insufficient if the turbine sections are at drag speed. Consequently, sampling had to be increased.

Engagement from HP/IP coast down

To simplify the analysis it was assumed that the LP turbine remains at 6Hz while the IP turbine coasts down. This is assured by the turning gear. Assuming an appropriate size of the turning gear the acceleration starts as soon as the HP/IP turbine coasts down to 7Hz. Figure 12 shows a successful engagement from LP turbine drag speed. Please note that the acceleration of the LP turbine can be much lower than standard acceleration in order to reduce the requirements for the size of the turning gear. The required driving torque of the turning gear could also be determined with the simulation model.

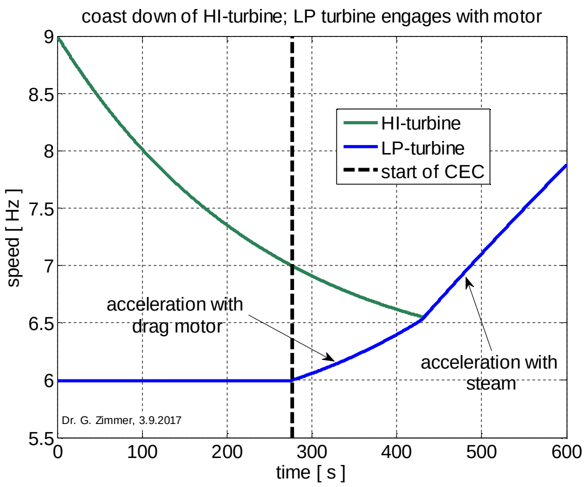


Figure 13 Engagement while HP/IP turbine coasts down

Prior to engagement, the LP turbine is accelerated with the turning gear. After engagement the acceleration is transferred to acceleration with steam.

Figure 14 and Figure 15 show details of the engagement depicted in Figure 13.

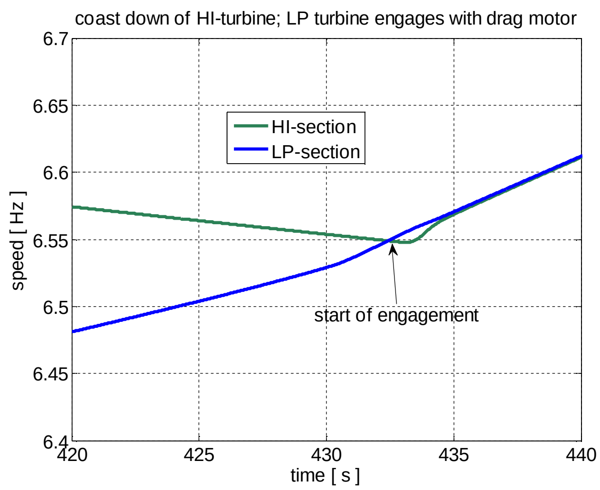


Figure 14 Engagement while HP/IP turbine coasts down; detail at start of engagement

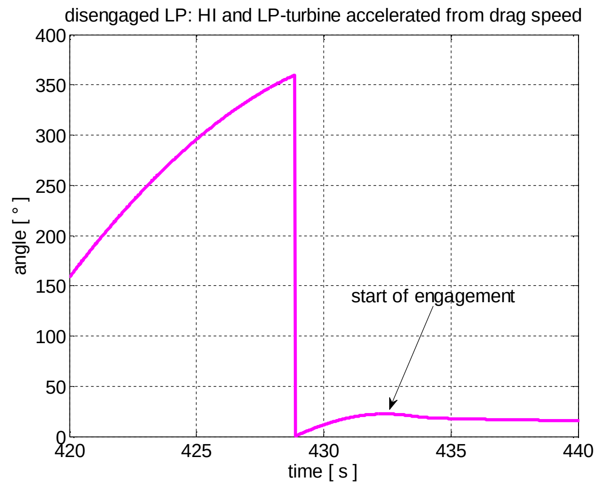


Figure 15 Angle difference at start of engagement from HP/IP-coast down, target angle is 0°

Figure 15 shows that the clutch angle engagement controller is also able to operate with the turning gear. The achievable difference between the target angle and the obtained angle is less than 10°. This is sufficiently close to the achievable accuracy of around 5° which is the design limit.

Engagement from HP/IP- and LP turbine at drag speed

In Figure 16 the ability of the turning gear to engage the LP turbine to the HP/IP turbine while both sections start at their respective drag speeds is demonstrated. This represents steam turbine bypass operation with disengaged HP/IP- and LP section. The gas turbine is running at nominal speed. This covers the unlikely event that the engagement of the LP turbine from HP/IP coast down (see Figure 13) has failed.

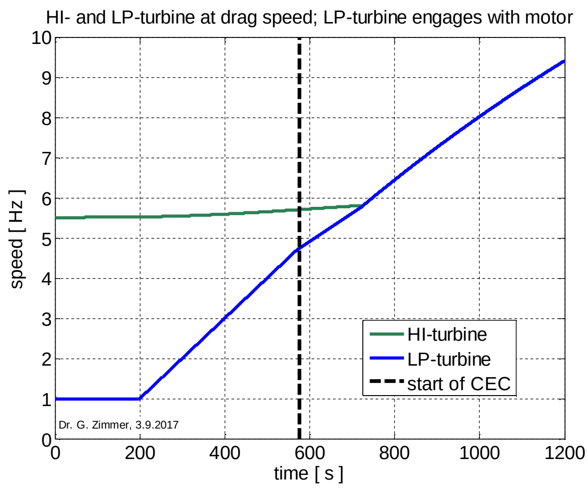


Figure 16 Engagement while both steam turbine sections are at drag speed

Figure 16 shows that engagement from HP/IP and LP turbines at drag speed is also possible provided that the turning gear is sufficiently dimensioned. The achievable clutch angle at engagement is less than 10° off the desired position, too.

CONCLUSIONS

In order to positively affect the vibrational behaviour of a steam turbine shaft with a decoupled LP turbine it was investigated whether angle engagement control is feasible for the decoupled LP turbine. Two cases for clutch angle control were investigated: Case 1 was for engagement at nominal speed; case 2 was for engagement at drag or turning speed. A simulation model was developed to investigate feasibility and respective boundary conditions for different sizes of the intended start-up butterfly valve.

In case 1 the LP turbine speed is controlled by the LP SUV the analysis revealed requirements concerning the size of the LP SUV, the velocity of the actuator and the required pressure in front of the valve.

In case 2 the LP turbine speed is controlled by an electrically driven turning gear rather than with steam. The analysis revealed that successful application of the clutch angle control is also possible for this application also. By means of the simulation the size of the turning gear was dimensioned. Additionally it was shown that the required size could be reduced by reducing the nominal acceleration. This point was subject of an internal R&D project but is not elaborated in this contribution. The analysis further showed the need to increase the measurement frequency of the LP shaft speed for case 2.

Overall feasibility to implement clutch engagement control into a new CHP configuration with a single shaft gas and steam turbine and a mechanically decoupled LP is shown. This will allow future configurations that will enable maximum heat extraction at highest operational flexibility at stable vibration level and very high efficiency. This configuration is perfect in terms of fast response to changing demands at very low cost.

NOMENCLATURE

CCPP	Combined Cycle Power Plant
CHP	Combined Heat and Power Plant
GT	Gas Turbine
HP/IP	Combined High and Intermediate Pressure Turbine
HRSG	Heat Recovery Steam Generator
IP	Intermediate Pressure (Turbine)
LP	Low Pressure (Turbine)
LP CV	Control Butterfly Valve upstream low pressure turbine
LP SV	Shut-off Butterfly Valve upstream low pressure turbine
LP SUV	LP Start-up valve
n	speed
P	power output
SSS	Synchro-self-shifting clutch
TD	Turn Drive
Δn	speed difference
$\Delta\Phi$	angle difference
Φ	Shaft angle

PERMISSION FOR USE

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