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Controller Tests for Molten Salt Parabolic Trough Systems With Loop-Wise Control Valves

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Tim Kotzab[1,*], Niklas Dicke[1], Michael Wittmann[1], Mirko Meyer-Grünefeldt[1], Jana Stengler[1], Paula Martins[2], Pedro Horta[2], and Tobias Hirsch[1]

[1]German Aerospace Center (DLR), Institute of Solar Research, Germany

[2]University of Évora, Portugal

*Correspondence: Tim Kotzab, tim.kotzab@dlr.de

Abstract. Concentrated Solar Power systems are used to generate thermal and electrical energy from solar radiation. Molten salt as a heat transfer medium offers the possibility of a higher temperature in the solar field and at the same time the use of direct energy storage. The Évora Molten Salt Platform is a research platform to study molten salt in the solar field on a pre-commercial scale [1]. The use of molten salt requires to adapt control concepts used in thermal oil fields since the temperature rise over the loop and the loop length are different from those of thermal oil. One approach is to use automatic valves in each loop to individually control the temperature at the outlet of each loop. This paper presents controller tests performed at the HPS2 molten salt loop of the Évora Molten Salt Platform for normal operation and start-up mode that provide the basis for an individual loop flow control strategy.

Keywords: Parabolic Trough, Valve Control, Molten Salt

1. Introduction

Concentrated Solar Power (CSP) systems enable the generation of thermal and electrical energy from solar radiation. In order to generate thermal energy, the direct normal irradiance (DNI) of the sun's rays must first be concentrated in order to heat a heat transfer medium (HTF). The objective of this paper is to present a methodology for the control of the solar field of a parabolic trough power plant. The solar field is typically partitioned into multiple sub-fields, each comprising a comparable number of loops. A loop consists of several solar collectors, each of them driven by a separate motor to follow the position of the sun. The mass flow of the HTF is provided by a central pump for the entire solar field. Although a few plants with molten salt as an HTF in parabolic trough systems have been built the technology still is a R&D topic. The driving motivation is the increase in outlet temperature of the solar field, which can reach 500 to 565 °C depending on the salt mixture used. Standing for a temperature rise of 200 to 250 K in the solar field when compared to the use of thermal oil, as in existing parabolic trough plants, the use of molten salt as HTF allows for a higher overall plant efficiency.

Control concepts for molten salt systems with individual control valves in each loop are presented by [2], [3] using the dynamic simulation tool Virtual Solar Field (VSF) as a test bench. The tool [4] allows the simulation of an entire parabolic trough solar field, considering realistic irradiation conditions. In the control concepts for the solar field with molten salt, control valves were utilized for each loop, thereby enabling the mass flow rate to be set individually for each loop. The results illustrate the value of a detailed, dynamic simulation with realistic irradiation boundary conditions as a valuable tool for the investigation and evaluation of solar field control concepts. The evaluation has demonstrated that control valves can offer advantages in transient situations and in the presence of inhomogeneous soiling. As a consequence of the unavailability of a solar field for testing purposes, the validation of the concepts is only possible on test facilities, where only parts of the concepts can be evaluated. This is particularly the case for control concepts that affect several control loops, while only one control loop is available in the test system. In this paper, elements of the control concepts are tested on the HPS2 molten salt loop of the Évora Molten Salt Platform (EMSP) [1].

The HPS2 test loop, funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), industry partners, the Portuguese Science and Technology Foundation and the Regional Operational Program Alentejo2020, is integrated in the Portuguese National Research Infrastructure on Solar Energy Concentration and part of the jointly operated research infrastructure of the EMSP. Within the MSOpera and EuroPaTMoS project, the 3.5 MW_{th} parabolic trough plant with solar salt as HTF has been demonstrated and optimized. EMSP is co-managed by the University of Évora and DLR and aims at the development of applied research on the use of molten salts as heat storage media and/or HTF in energy applications. This infrastructure, also part of the ERIC EU-SOLARIS, disposes of two different molten salt loops: HPS2, a full-fledged solar loop with a 3.5 MW thermal power and a 5,4 MWh two-tank storage system; and NEWSOL, a solar decoupled 2.9 MWh molten salt thermocline tank. The activities reported in the present article took place in HPS2 loop.

2. Control-System for tests on the EMSP

The control system for normal operation is designed in a way that the outlet temperature in each loop is controlled as precisely as possible to the setpoint value by adjusting the valve opening. Since the final mass flow in the loop is determined by the valve opening of the respective loop and the overall pressure head imposed by the HTF pump, a well-balanced control concept for valves and pump is required. The underlying idea is to adapt the overall mass flow to the field when valve openings change systematically. For example, if the temperature in each loop of a solar field is too high, the valve at the inlet of each loop is opened to increase the required mass flow. This short-term reaction of the loop control has to go along with an adjustment of the overall mass flow to the solar field. As soon as the mass flow has been increased the valve openings can be reduced again to their nominal operating point. The aim of this method is to prevent a general drifting of the valves and associated loss of controllability [3].

Since a multi-loop system was not available for testing the control concept, the molten salt loop at EMSP is used. Although the parallel loop control configuration cannot be tested it is the intention of the single loop control tests to validate the individual mass flow control concept for the loops. Given the pre-requisites of the EMSP loop the mass flow to the loop is directly adjusted by controlling the main salt pump. The general control concept is therefore validated with the control structure, whereby only the mass flow in the loop is adjusted.

Figure 1 shows the **normal operation control scheme** used for the tests at the EMSP. The actual error (e_T) is calculated from the measured outlet temperature ($T_{loop,out}$) and the setpoint temperature ($T_{loop,req}$). The error is used as the basis for the proportional-integral (PI) controller in the valve control section. This controller is used to calculate a delta for the change in valve opening (Δs_v) that would be required to reach the outlet temperature. Whereas this signal would be sent to the loop control valves in a multi-loop configuration, the opening in the simplified test setup directly serves as input to the mass flow PI controller. The controller determines the new required mass flow ($\Delta \dot{m}$), which is added to the base mass flow ($\dot{m}_{Base}$) and then used as controlled input to the EMSP control system. An anti-windup mechanism is employed to reduce the integral component of the controller as soon as the calculated output variable exceeds or falls below the maximum or minimum permissible valve opening or mass flow.

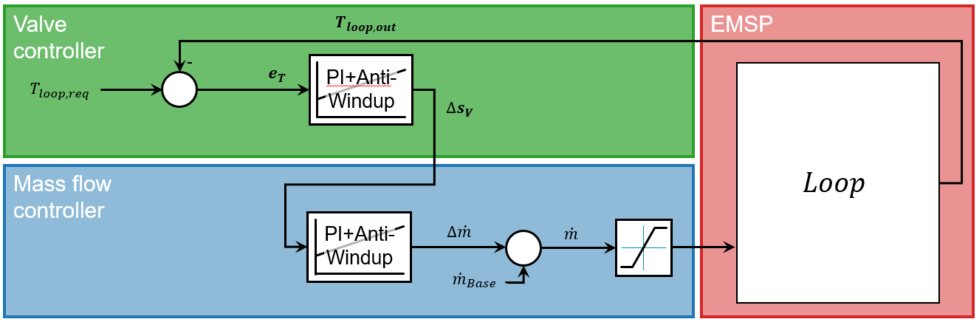

Figure 1. *The control concept for the normal operation of the solar field based on valve control, which is adapted to the conditions of the EMSP.*

The purpose of the **startup controller** is to increase the temperature of the solar field from its current value to the specified design outlet temperature. The temperature gradient-based start-up concept is demonstrated by operating the EMSP collector loop with a fixed valve opening and varying HTF pumping power. **Figure 2** depicts the configuration of the control structure utilized in the experimental tests. The temperature gradient within each control time step is determined by means of the equation 1, taken from [2], which serves as the basis for comparison with the temperature gradient setpoint ($\Delta T_{loop,req}$).

$$\Delta T_{loop} = \frac{2.75 \cdot \Delta T_{max} + 1.25 \cdot \Delta T_{mean}}{4} \tag{1}$$

Here, ΔT_{max} represents the maximum and ΔT_{mean} the average calculated temperature gradient of all sensors within the loop. The resulting error (e_T) is employed to calculate a new mass flow ($\Delta\dot{m}$) in the PI controller. This new mass flow value is then added to the base mass flow ($\dot{m}_{Base}$). The controlled mass flow ($\dot{m}$) is provided as an input to the EMSP plant control, which subsequently sets the pumping speed accordingly.

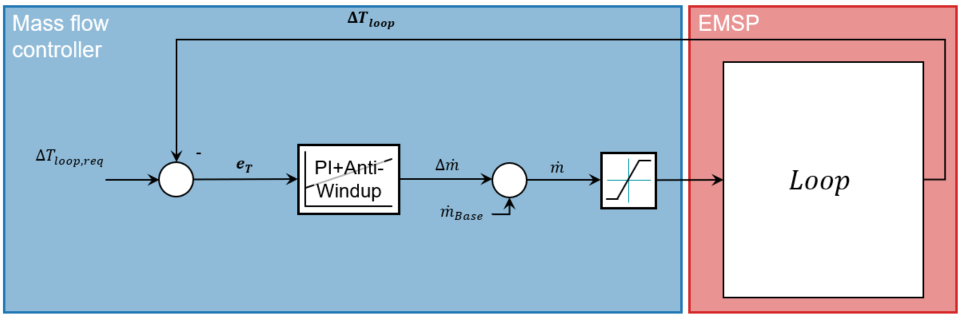

Figure 2. *Control structure for the tests at EMSP based on the temperature gradient based control approach*

The control concept tests were conducted in August and September of 2023. The following experimental boundary conditions must be considered for interpreting the results:

- Due to a temporal outage in the steam generator unit, the hot salt could not be actively cooled via the steam generator. Instead, the salt was slowly cooled down over-

night by pumping it through the solar field. This meant that the maximum temperatures in the solar field were reachable. For the start-up tests, subsequent tests with a desired temperature rise 50 K are executed.
- The solar field was prepared in manual mode for the tests. This means that a fixed mass flow was set and the collectors were moved into focus. As soon as test conditions have been reached, the system was switched to controlled mode and a test was carried out.
- To avoid direct interaction with the EMSP control system, an OPC-UA interface was implemented. The relevant sensor signals are read out via the OPC-UA interface. The new mass flow for the loop is then calculated and fed back to the control system via the interface. Next, the new mass flow is adjusted internally in the control system by changing the pump speed. This is done by means of an integrated mass flow controller, which adjusts the pump speed accordingly until the new setpoint is reached.

3. Results

A total of eight tests were conducted to assess the system's **normal operational** functionality. These tests included an initial adjustment of control parameters and an analysis under clear sky conditions. The results of a test with clear sky conditions are presented in Figure 3.

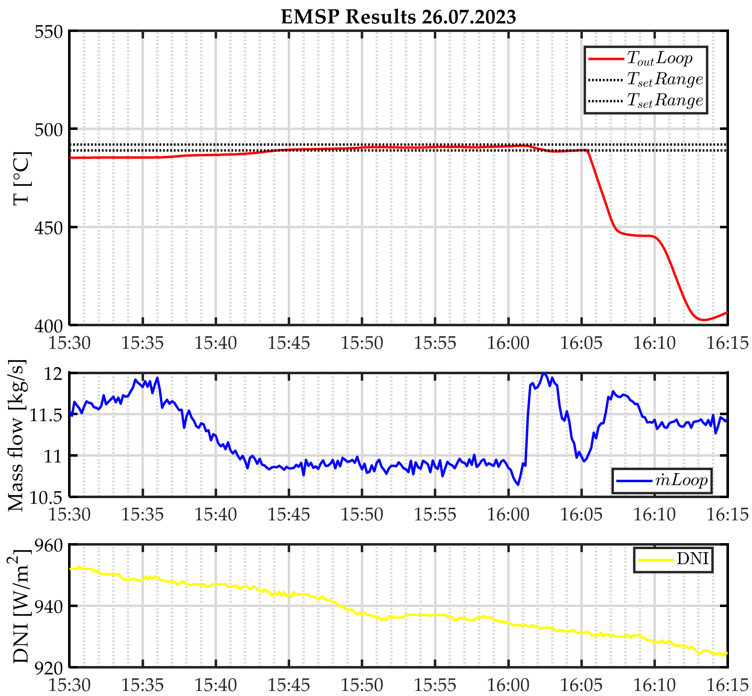

Figure 3. *Control test for normal operation. The controller takes over at 15:35 at a temperature of 485 °C and ends at around 16:00.*

Figure 3 illustrates the measured loop outlet temperature and the design temperature range. Additionally, the mass flow into the loop and the measured DNI are illustrated. The loop was initiated manually by positioning the collectors into the focus and defining the mass flow. The control system was activated at 15:35 with the objective of controlling the temperature within the specified range between 489 °C and 492 °C. The control system remained operational until 16:00, and was then deactivated. Subsequently, the mass flow was manually adjusted, and the collectors were moved out of focus, resulting in a decrease in temperature at 16:05. Upon activation of the controller, the mass flow was reduced, resulting in an increase in outlet temperature to values within the setpoint range. The Root Mean Square Error (RMSE) from the design temperature of 490 °C is calculated for the purpose of evaluation. In this test, the RMSE is 0.94 °C or 0.19 %. At the beginning of the test, the difference between the actual and setpoint values was minimal, necessitating a slight adjustment of the mass flow. In the present test, the mass flow was adjusted in a robust way, ensuring that no temperature overshoot above the setpoint occurred.

Similar tests under clear sky conditions have been executed. The RMSE values for all test days of normal operation in clear sky conditions were found to be 0.95 °C or 0.18 %. This indicates that the control system effectively controls the temperature to the setpoint in clear sky conditions. In one instance, a temperature overshoot of 1.3 °C was observed. This was promptly adjusted, and the temperature was subsequently controlled back into the setpoint range.

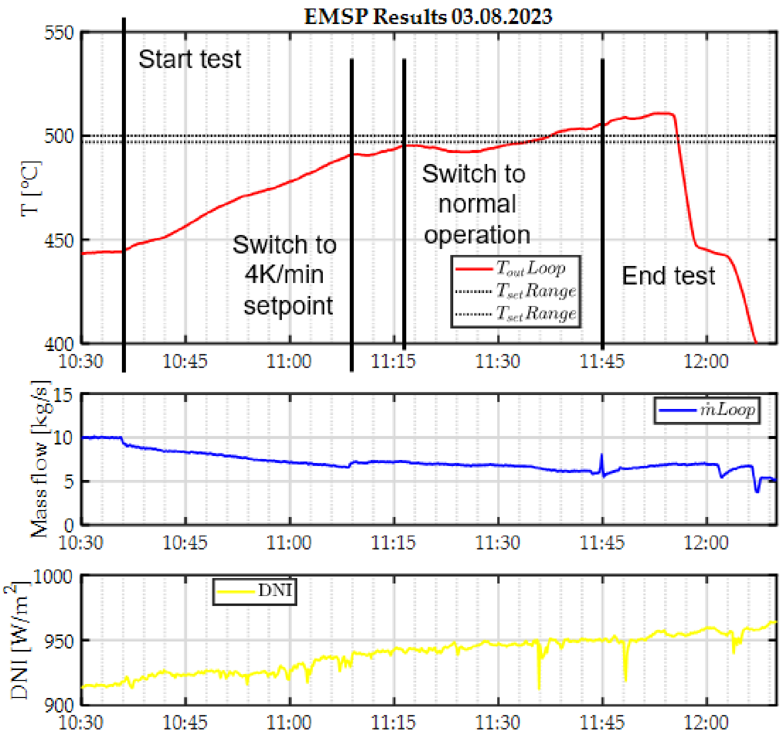

Figure 4. *Control test for start-up. Temperature gradient setpoints according to Figure 5 (10 K/min then reduced to 4 K/min). The start-up procedure in this example starts at 440 °C and ends when reaching the threshold for switching into normal operation at around 11:15.*

Tests for the **start-up** were carried out over a total of 5 days. The functionality of the control concept was tested in clear sky situations. One test involved a cloudy situation, which can test the functionality of the start-up control system in transient situations. The objective of the tests is to achieve the set point for the outlet temperature in the shortest possible time without significant overshoots. It was observed during the course of the tests that the most optimal results were achieved when the temperature gradient setpoint value was adapted when approaching the end of the start-up phase. While the standard temperature gradient setpoint is 10 K/min, it is reduced to a value of 4 K/min as soon as an outlet temperature of 485 °C is reached, as illustrated in Figure 5. The resulting start-up procedure on the test day of August 3 is illustrated in Figure 4. The temperature is increased from 440 °C to 490 °C in approximately 25 minutes with a gradient of 10 K/min. As soon as the transition temperature of 485 °C is reached the gradient is reduced to 4 K/min. This is intended to prevent the temperature from exceeding the desired target outlet temperature. The effect can be observed in Figure 4 at approximately 11:10. At this point, the temperature limit of 485 °C is reached, and the controller transitions from a temperature gradient of 10 K/min to 4 K/min. Consequently, the mass flow is increased, and the temperature rises at a lower rate. The intended startup controller on this example day is completed at approximately 11:15, at which point the system transitions to normal operation at a temperature of 490 °C. Following start-up mode, the control concept for normal operation mode becomes active. Control is maintained until approximately 11:45, at which point the control system is deactivated and the operator on site assumes control of the system. The operator did not deliberately approach the temperature of 500 °C; instead, they moved the collectors out of focus shortly thereafter, thereby terminating the energy collection process.

Figure 6 illustrates the results of a test conducted in a cloudy situation. At approximately 13:15, the control system was activated. At this time, the system is operating within normal operation under mostly clear sky conditions. In this period up to approximately 13:40, the RMSE is 1.41 °C or 0.27%. The condition for transitioning between start-up and normal operation is represented by the variable $T_{set,switch-start-up}$ in the figure. If the temperature is below the specified threshold, the start-up procedure is active. At 13:40, the presence of clouds over the EMSP is indicated by the DNI. This cloudy condition is present until approximately 14:15. The test continued until approximately 14:30, at which point the controller was deactivated and the operator on site took over manual control.

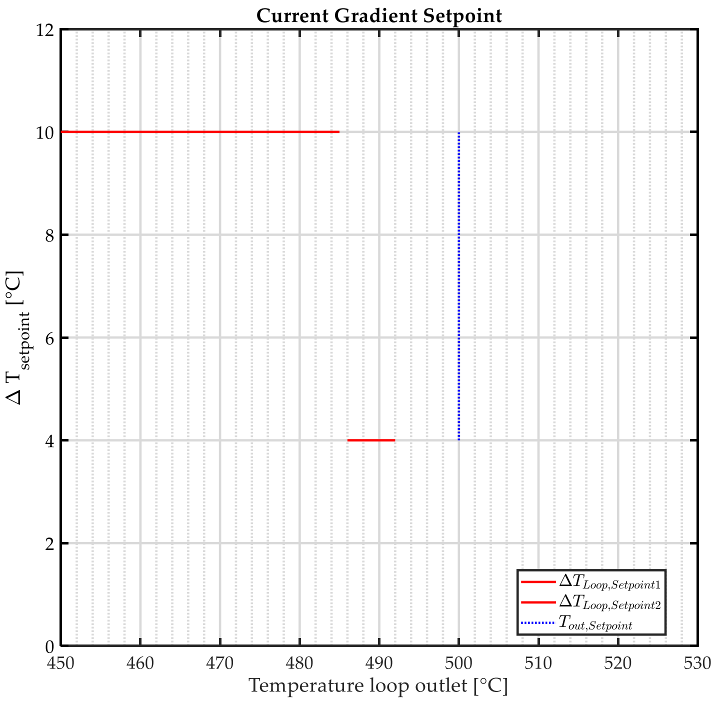

Figure 5. *Set point for temperature gradient.*

With the start at 13:15, the control system is in normal operation and controls the temperature to the setpoint of 515 °C. At around 13:40, the first clouds appear, causing the DNI to drop to almost 0 W/m^2. This causes the outlet temperature in the solar field to drop. The control system reacts at this moment by lowering the mass flow. The mass flow is further adjusted and the controller switches to the start-up process. Then there is a short period in which the DNI is fully present again from approx. 13:40 to 13:50. Here the temperature rises above the setpoint. The control system tests only used the loop outlet temperature as measured signal. Applying additional temperature limits on collector level would have reduced the overshoot in temperature and is recommended to be used in future configurations. At 13:50, the temperature declines below the threshold for transitioning between start-up and normal operational modes. This is due to a reduction in DNI resulting from cloud cover. Consequently, the start-up control system is initiated. A transition from normal operation to start-up mode results in a reduction in mass flow, which is necessary to facilitate the reheating of the solar field. As soon as sufficient DNI is available, the temperature rises again and the mass flow is increased by the start-up controller until the system switches to normal operation. After 14:00, the scenario is repeated and the controller reacts immediately by adjusting the mass flow to the situation. An important point of the test was to check whether the entire control system behaves stably. This means that the control system calculates suitable mass flows and does not oscillate. This would be the case if the mass flow had very large jumps and ran into the limits. In this experiment, the mass flow was calculated for the situation in order to bring it back to the setpoint temperature as far as possible. The control system did not become unstable during the test period from 13:40 to 14:30.

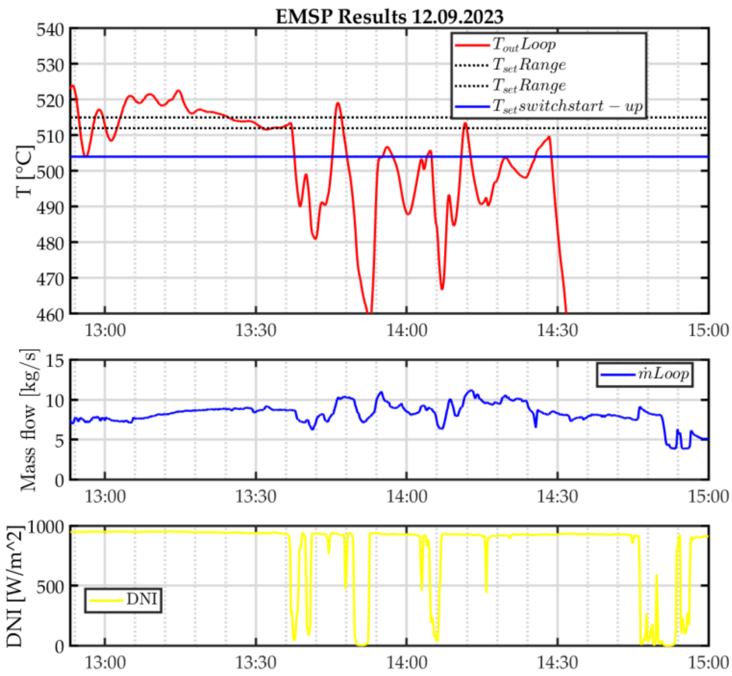

Figure 6. *Controller test for start-up and normal operation with cloudy situation. The controller was initiated at 13:15 and remained active until 14:30.*

4. Conclusion

The HPS2 molten salt test loop has been used to execute controller tests for a loop-wise control concept. The prevailing conditions at the HPS2 did not allow to carry out start-up tests covering a full range of 200 to 250 °C temperature rise. Also, only a limited number of tests was able in the testing period.

The experimental tests conducted to assess the normal operational functionality of the system have demonstrated its ability to effectively control the temperature within the specified range under clear sky conditions. The results show that the control system successfully maintained the outlet temperature within the desired setpoint range, with a RMSE of 0.95 °C or 0.18 % on average. This level of precision is indicative of robust performance and minimal deviation from the setpoint. Furthermore, the control system's ability to adjust the mass flow in response to minor deviations has been demonstrated, ensuring that no significant temperature overshoot occurred during testing. These findings provide strong evidence that the system is capable of reliable operation under normal conditions, making it suitable for practical applications.

Start-up procedures with a temperature gradient of 10 K/min have been executed. It is demonstrated that the reduction of the temperature gradient to 4 K/min when approach the set point temperature is able to avoid overshoots. The results of the test with two temperature gradients also demonstrate a smooth transition between the two regions. The results of this study can be extrapolated to other solar fields. Whereas the maximum gradient values are usually prescribed by the manufacturers the best value for the reduced temperature gradient is determined through testing at the EMSP. With regard to other systems, it would be reasonable to test whether identical values can be applied. The tests conducted under clear-sky conditions were successful, ensuring a smooth startup. Furthermore, the system was successfully driven to the set point.

A further test was conducted in conditions of intensive cloud cover. This test involved switching between the start-up control mode and the normal operation control mode several times. In the present investigation, it was demonstrated that the control system exhibits a high degree of stability even under the given, unstable conditions. The mass flow was adjusted in accordance with the respective situation, with no mass flows that could potentially result in unstable behavior being calculated. Additional testing under transient conditions would be beneficial for a more comprehensive evaluation of the control system.

Data availability statement

Data can be requested from the authors.

Author contributions

Tim Kotzab: Conceptualization, Methodology, Writing-Original Draft, Visualization. **Niklas Dicke:** Writing-Review and editing. **Michael Wittmann:** Writing-Review and editing. **Mirko Meyer-Grünefeldt:** Writing-Review and editing. **Jana Stengler:** Writing-Review and editing. **Paula Martins:** Writing-Review and editing. **Pedro Horta:** Writing-Review and editing. **Tobias Hirsch**: Conceptualization, Methodology, Writing-Review and editing, Supervision.

Competing interests

The authors declare no competing interest.

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