Deliverable 5.3

Hardware-in-the-loop testing of mGT

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1. Introduction

Hardware-in-the-Loop (HiL) testing is a key methodology for validating and commissioning complex control systems before they are deployed in real-world operation. Modern control architectures typically integrate multiple subsystems with varying priorities and hierarchical interactions. As a result, ensuring correct system behaviour prior to field operation is essential, particularly for advanced applications such as high-performance micro-gas turbines (mGTs)) [1, p. 6].

HiL provides a controlled environment in which real hardware components interact with a high-fidelity real-time simulation of the remaining plant. This setup acts as a *digital twin*, allowing the development team to test, optimize, and iteratively refine control strategies at a very early stage of the development cycle. By detecting errors and inconsistencies long before commissioning, HiL significantly reduces project risks and overall development time.

Key advantages of the HiL approach include:

- **Reduced commissioning costs:** Issues can be identified and corrected before on-site testing begins, avoiding expensive hardware damage or downtime.
- **Enhanced safety:** Critical states and extreme operating conditions can be tested without endangering personnel or equipment.
- **Accelerated development and optimization:** The digital twin environment enables rapid iteration, parameter tuning, and scenario testing that would be impractical or unsafe on the real system.
- **Improved system robustness:** Comprehensive testing ensures the control system performs reliably under a wide range of operational scenarios, including fault conditions.
- **Application-specific adaptability:** HiL facilitates targeted development for different operating strategies or configurations.

This Deliverable focuses on the HiL testing of the combustor test stand at OWI. The test configuration (Figure 1) included the MITIS combustor integrated with the heat exchanger, water injector (to simulate the effects similar to that of the micro-gas turbine), air supply, fuel supply system, and all relevant sensors and actuators. The purpose of including the water injector after the combustion chamber was to reduce the temperature of the exhaust gases after the combustion process to a suitable level ($\leq 750\,°C$), such that the maximum temperature limit at the recuperator inlet is not exceeded as per the system specifications.

Through HiL testing, the behaviour of the integrated system could be assessed under realistic dynamic conditions while enabling safe, efficient, and repeatable optimization of its control strategies.

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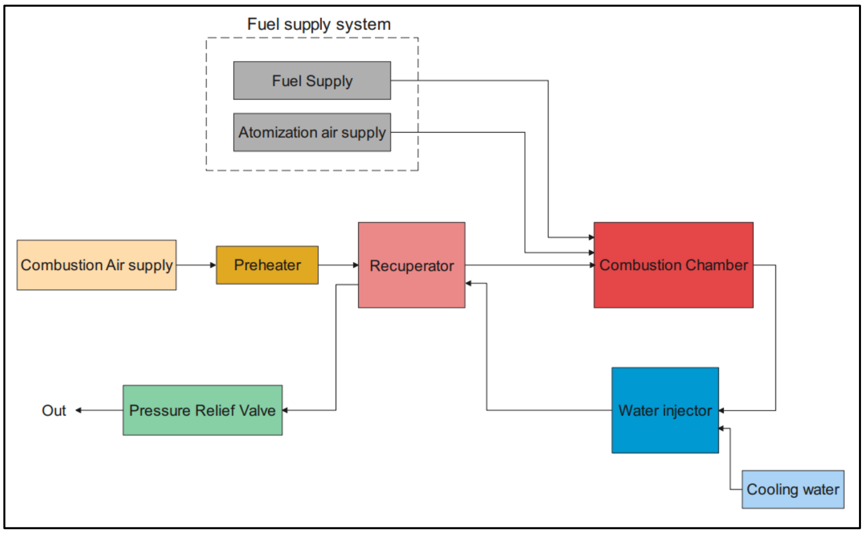

Figure 1: Components of the plant system (block diagram).

2. Methodology

The complete control system, i.e. the target controller and its peripheral modules, along with the user-interface, was iteratively tested for all the defined operating modes and checked for possible error occurrences. Following the V-Model testing procedure, Model-Based-Systems-Engineering (MBSE) approach was implemented to create and validate the control system at each stage of its development. As shown in the **Error! Reference source not found.** below, the testing procedure consists of testing phases at different hierarchical levels of the control system development process [2, p. 8].

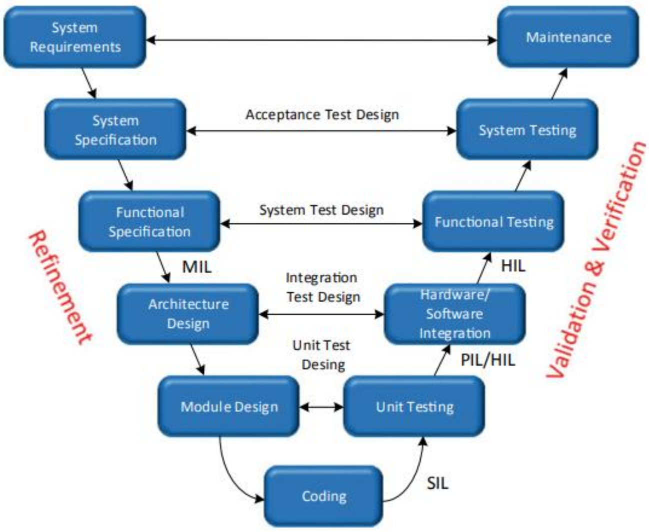

Figure 2: Model development, refinement, and validation depicted in the V-Model [1, p. 3].

The early stages of testing are involved with creation and validation of the control algorithm, that is later extracted and deployed inside a hardware controller. The Software-in-the-loop (SiL) testing process was first undertaken to test the control algorithm inside a digital software environment, namely MATLAB and

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SIMULINK. In order to validate the control algorithm, a virtual twin of the plant was created to emulate the static and dynamic behavior of the real plant as shown in Figure 3.

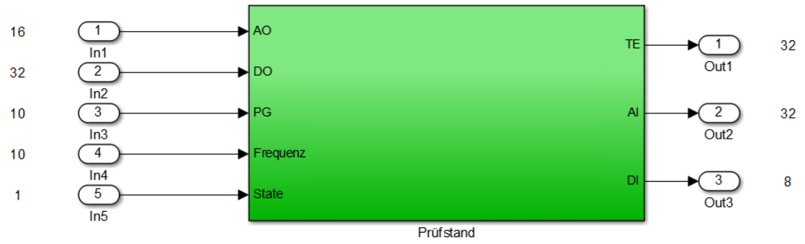

Figure 3: Plant model created with Simulink.

The plant model consisted of mathematical models of real plant components, for example, heat exchangers, pumps, combustion chamber, etc. programmed as SIMULINK subsystems. The SIMULINK models were interfaced together to replicate the structure of the real plant system with its individual components. In a similar way, the virtual twin of the controller was also created (without the GUI), with the inclusion of its essential functional blocks, for example, a Mealy state machine, triggered SUIMULINK subsystems for each operating state, PID Controllers with saturation and gain scheduling, output regulation system for the actuating signals, and an error detection and assessment system as shown in the Figure 4.

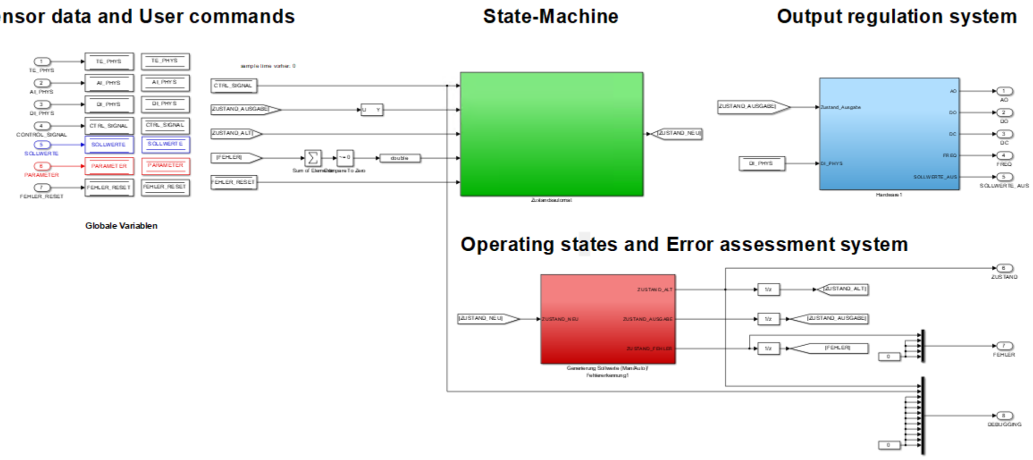

Figure 4: A visual breakdown of the components of the controller model.

The virtual models of the plant and the control system were created inside the same software environment as individual models, and these models were interfaced together in a closed loop, such that the controller could receive and react to the feedback from the plant response as shown in Figure 5. The main aim of testing at the SiL stage was to eliminate the logic and programming errors, unsupported interfacing, configuration errors, etc. at an early stage.

The benefits of testing at the SiL stage included robust control algorithm development, accelerated testing procedure, controller performance optimization, comparing different control strategies, as well as creating a reference validation data set for the HiL tests [3].

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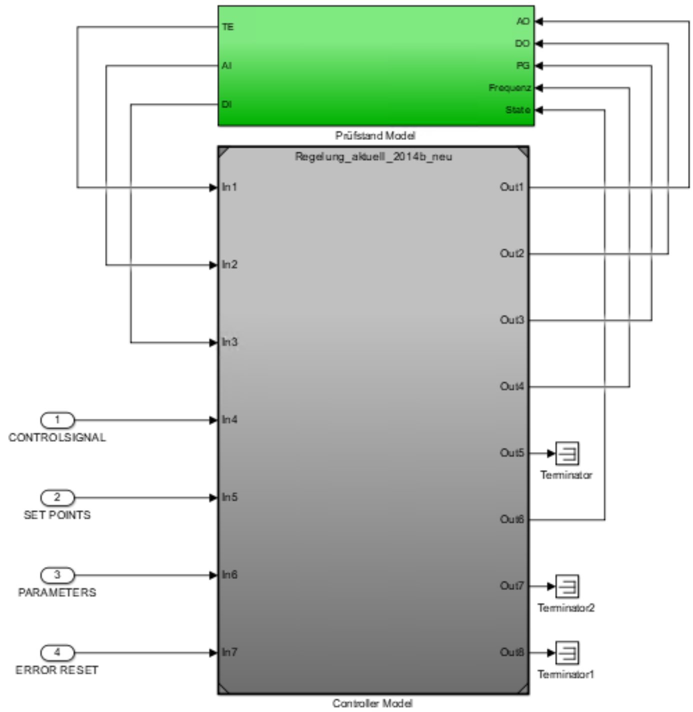

Figure 5: Virtual test bench model in Simulink: Interfacing of the plant model (top) and the controller model (bottom) to emulate the virtual test bench model, maintaining the isolation between them to test their individual functionalities.

HiL was the final testing stage of the controller development process before the control system was commissioned. The tested control algorithm at the SiL level was extracted and deployed inside the target controller, Figure 6 shows the deployment process for the HiL testing. The target controller chosen for the application was NI-CompactRIO edge controller, which was programmed using NI-LabVIEW [4]. The complete tool chain of the control system consisted of a LabVIEW architecture enabling data acquisition in real-time, the SIMLUNK-extracted embedded control algorithm inside the controller's CPU, and the user-interface. This approach was chosen to be able to integrate the individual advantages of three tools: MATLAB, SIMULINK and LabVIEW. LabVIEW enables configuration and programming of advanced, flexible edge controllers from National Instruments [5]. These hardware controllers are best suited to handle the dynamic and real-time control requirements of a complex system such as a micro-gas turbine with their configurable Field Point Gate Arrays (FPGA), inbuilt virtual systems, and additional hardware modules with their incredibly fast sampling rates and actuation times. One of the other main advantages of using LabVIEW was the feasibility in developing a customizable user-interface, and to seamlessly connect it with the data acquisition system of the controller. However, MATLAB and SIMULINK were chosen as the software environments for developing the control algorithm because these tools enabled not just the creation of a very sophisticated control strategy but also enabled the validation of its performance early on through SiL tests, with the help of the virtual twin model of the plant.

Therefore, the state-of-the-art control system was a combination of many subsystems interacting with each other. The main aims of HiL tests were to test the communication between these different subsystems at different hierarchical levels, as well as the functionality of the complex control system for all defined operating modes.

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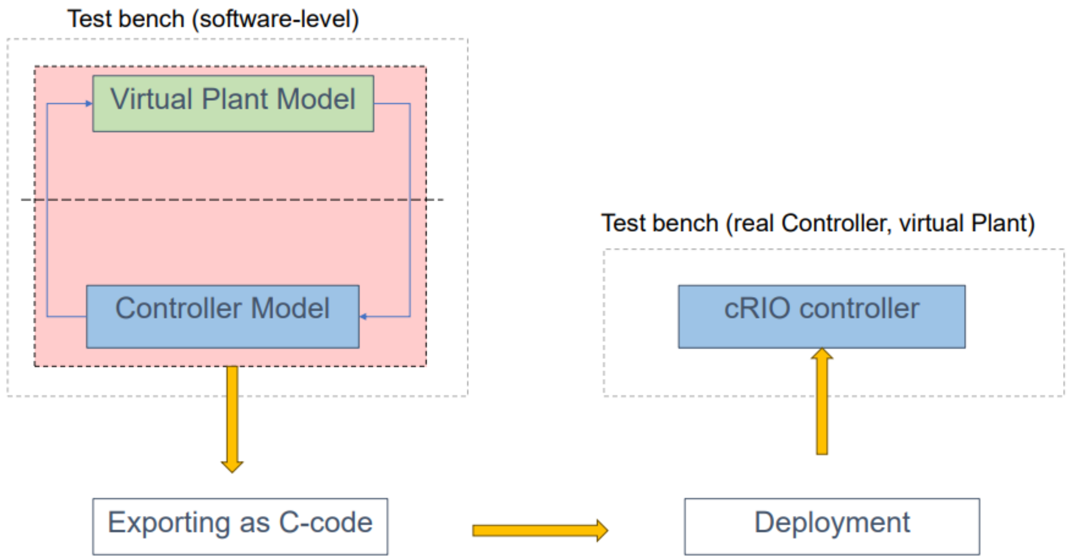

Figure 6: Process of deployment of the Extracted code of virtual test bench onto the hardware controller for HiL testing.

3. Results

The validation of the control algorithm was carried out first in the MATLAB and SIMULINK environment with the help of the virtual twin model of the plant. The performance of the control algorithm was analyzed for all the given operating modes of the plant. This initial testing concluded obtaining important results, such as identification of important control variables of the plant and their optimal setpoints, sensitivity of control parameters to the transient behavior of the plant, etc. Each of the control algorithm subsystems viz. the state machine, triggered operation state systems, output regulation system, and error assessment system were tested for their individual as well as combined performance.

The Section 3.1 shows the results of the testing process in detail for each operating mode of the test bench. Please note that the purpose of the virtual twin of the plant was not to replicate the results of the real plant system as they are, but to test the dynamic response of the control algorithm. For example, the water injector in the plant system also served the purpose of emulating the behavior of the gas steam interacting with the micro-gas turbine, especially to introduce reduction of the temperature of the exhaust gases and a pressure drop across the component. For example, the water injector in the plant system also served the purpose of emulating the behavior of the gas steam interacting with the micro-gas turbine, especially to introduce reduction of the temperature of the exhaust gases and a pressure drop across the component. Apart from the results discussed in this section, many more iterative tests were conducted with varying plant parameters in order to develop a control algorithm that was not just robust, but also pragmatically applicable in case of the actual mGT plant.

3.1. Software-in-the-loop testing of the control algorithm with the virtual twin of the plant

The SiL test results discussed in this section would encompass the results of the performance of the control algorithm in the following operating modes: transition to full load application (FULLLOAD) through partial load application (PARTLOAD), and the transition to FULLLOAD directly. Moreover, the dynamic fault handling of the system is also shown by discussing three cases of failure occurrences (through manual injection of errors in the system deliberately, while the system simulation was running). The performance of the control

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system to mitigate the effect of these errors and switching to a safe operating mode through an emergency stop automatically will be discussed in this chapter.

3.1.1. PARTLOAD to FULLLOAD Operation – Automatic operation mode 1

The start-up phase of the mGT was simulated by injecting the combustion air, fuel and the atomization air inside the combustion chamber (CC) and carrying out the 0D combustion reaction numerically in SIMULINK. It was crucial to analyze the combustion process, because within the first 250 seconds of the start-up, the high revolutions of the compressor shaft of the mGT drew in high amounts of air (oxidizer) into the system. To achieve a successful and stable combustion, the controller was tested to promptly react to the dynamically changing plant variables and adjusted the inputs of the plant in real-time, such that that desired setpoints for the controlled variables of the plant were maintained. The system was then ramped up gradually through multiple stages marked by the change of the temperature setpoints of the CC in Figure 7, until the full load capacity was reached (all the plant variables reached at their nominal operating values). During the full load application, the steady-state response of the plant, as well as the performance of the controller, was observed. The desired setpoints for the fuel and the air flows (as shown in the Figure 8), and the temperature profile were achieved during the complete duration of the test. The controlled plant variables included the temperature at the outlet of the CC, the temperature at the air inlet of the recuperator, the fuel and atomization air mass-flowrates, and the pressure at the outlet of the CC.

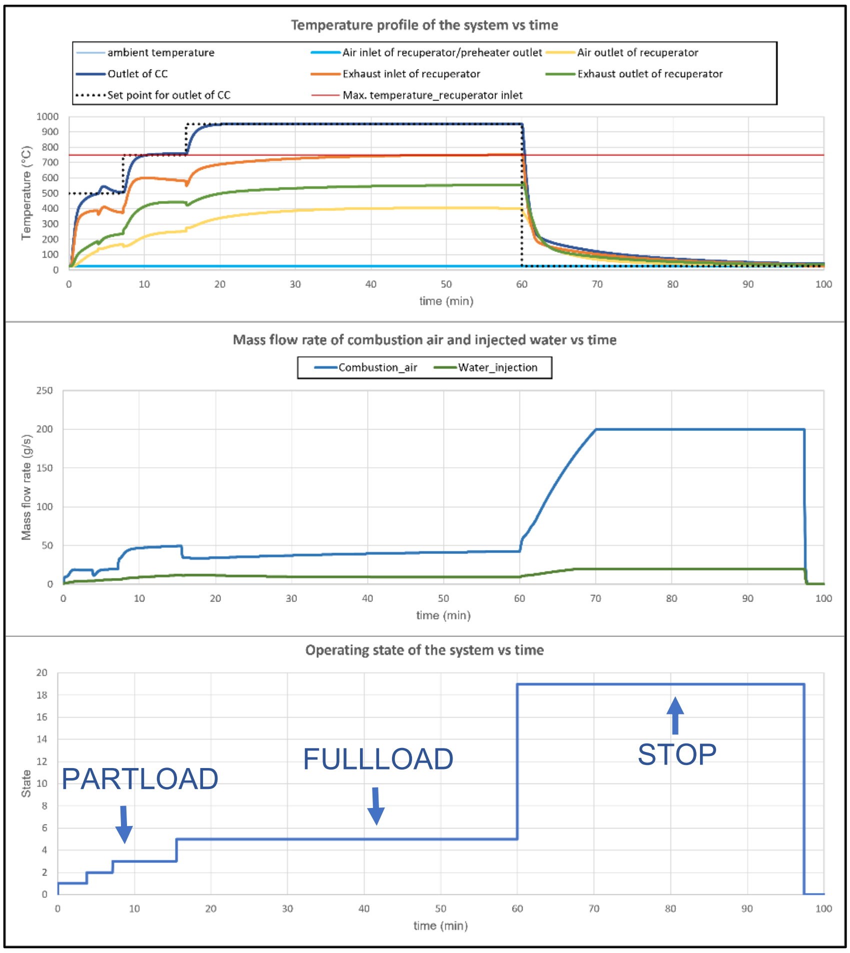

Figure 7: Temperature profile of the system (top), combustion air and water injection (middle) w.r.t. operation state (bottom) respectively.

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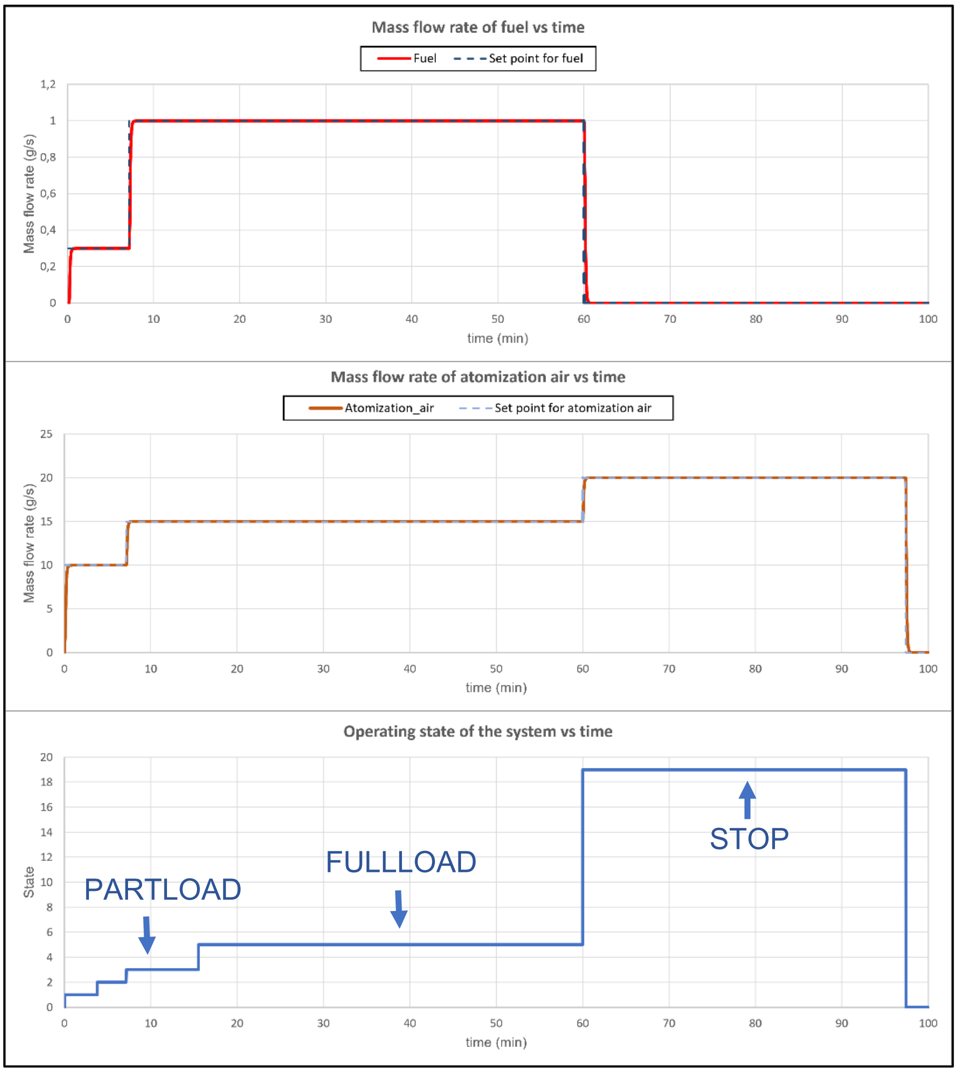

Figure 8: Fuel (top) and atomization air (middle) flow w.r.t. operation state (bottom) respectively.

3.1.2. Direct FULLLOAD Operation – Automatic operating mode 2

Obtaining the first SiL-test results (as shown in Section 3.1.1), it was clear that the controller performed very well in case of staged combustion process, gradually ramping up from the start-up until it operated at its full load capacity. To save time and costs during the operation and to reach the desired nominal operation point as quickly as possible, it was essential to inspect if the system could be ramped up to the full load capacity through an initial intermediate state from the start-up phase itself.

As shown in Figure 9 and Figure 10, the controller performed very well and maintained the desired setpoints for the controlled variables of the plant. The transient response of the plant showed a smooth transition to its full load operating capacity, while maintaining the plant's stability.

The analysis of the pressure profile was also very crucial for the safe operation of the plant. As shown in the Figure 11, the pressure control valve promptly reacted to the pressure levels changing in the outlet of the CC (due to the high air flow during the start-up phase) by varying its opening percentage to control the amount of air passing through it and building the desired back pressure. The results showed that although some pressure surges were observed (due to the numerical simulations), the control algorithm did control

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the pressure control valve in order to maintain the desired setpoint of the pressure at the outlet of the CC correctly.

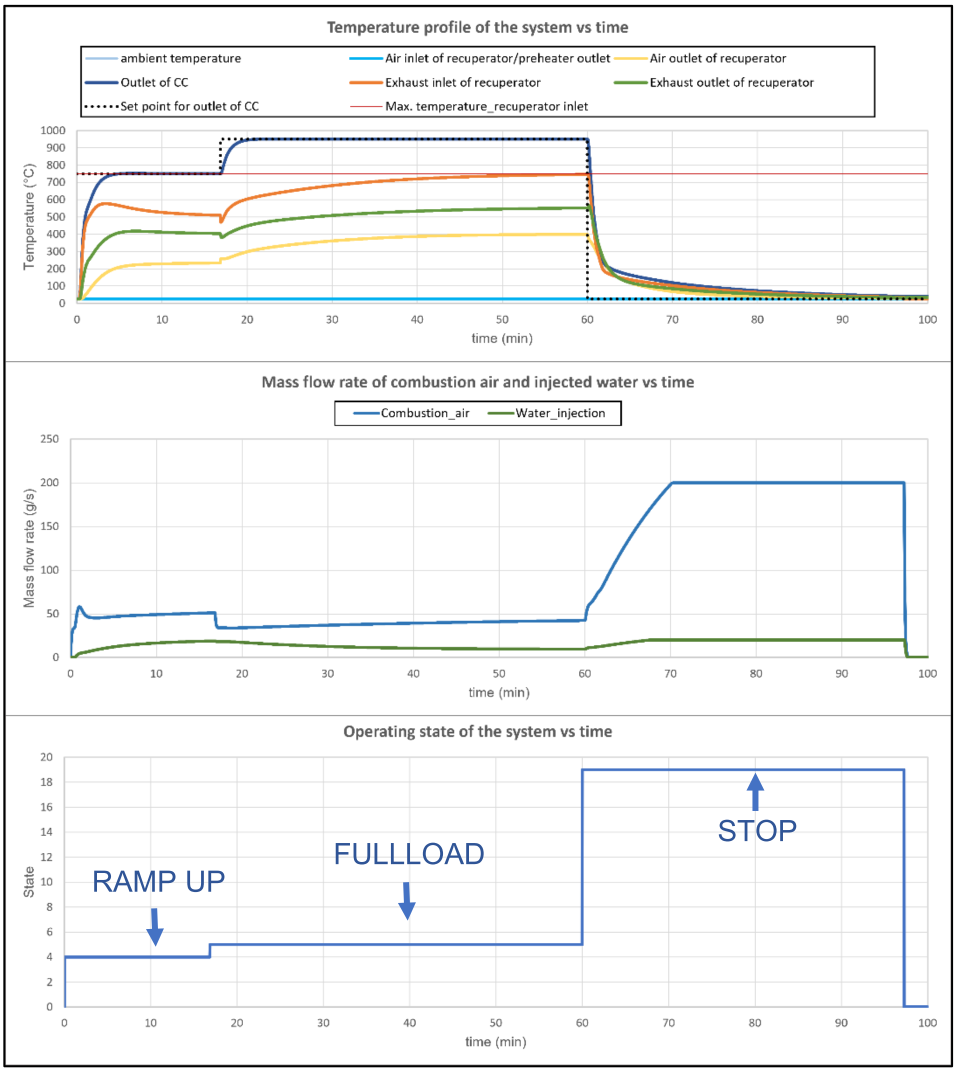

Figure 9: Temperature profile of the system (top), combustion air and water injection (middle) w.r.t. operation state (bottom) respectively (direct full load operation).

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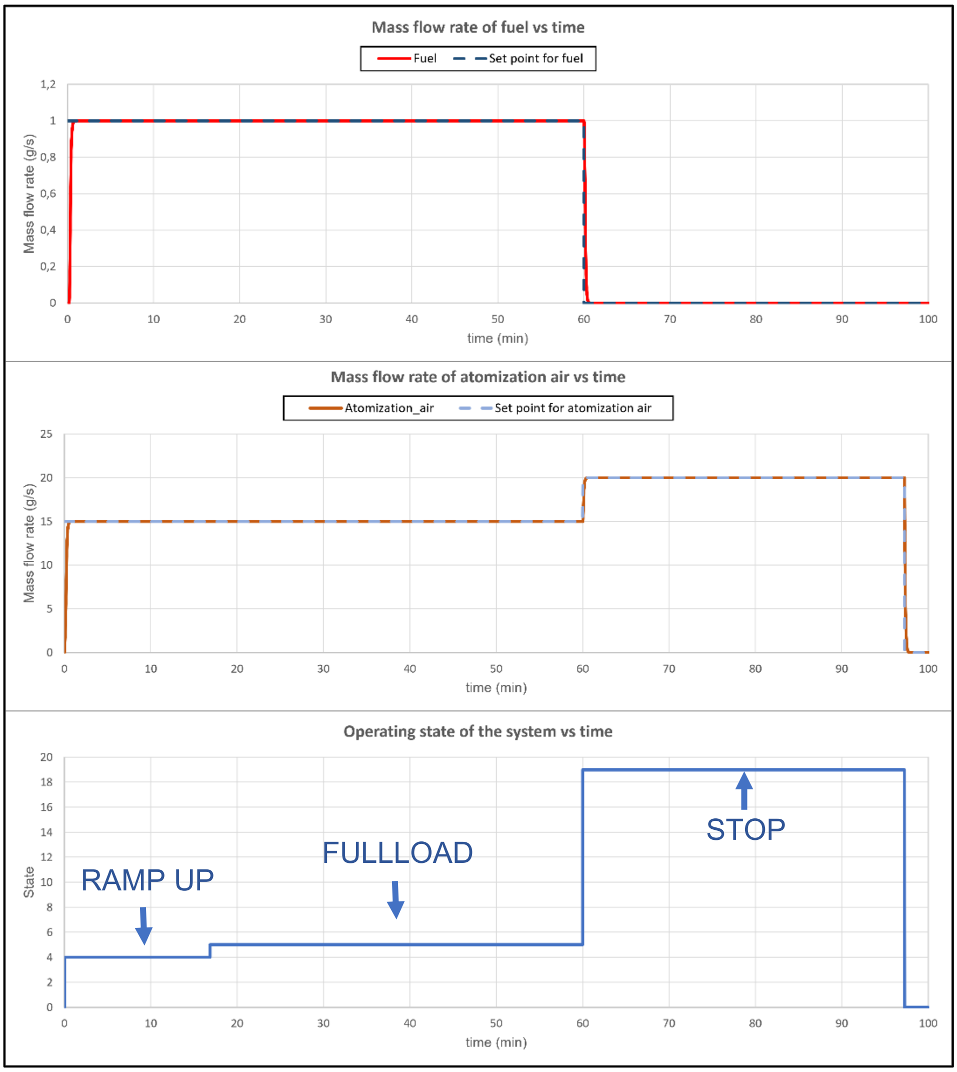

Figure 10: Fuel (top) and atomization air (middle) flow w.r.t. operation state (bottom) respectively (direct full load operation).

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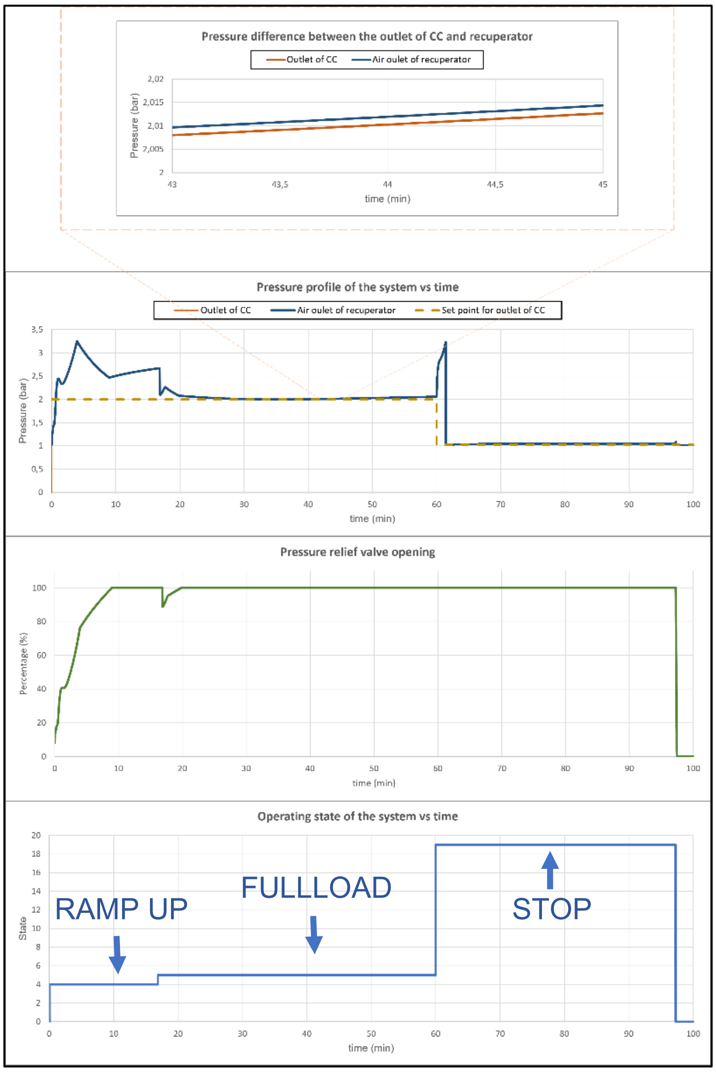

Figure 11: Pressure profile at the outlet of the CC and the air outlet of the recuperator (top) and the response of the pressure control valve of the plant (middle) w.r.t. operation state (bottom) respectively (direct full load operation).

3.1.3. Dynamic Fault Handling

Three failure cases are shown in this section. The response of the controller to mitigate the effects due to the failure occurrences and switching to a safe operating mode, if the failure condition continues to persist are explained in detail.

In Figure 12, as the air supply to the system is manually cut-off (bottom-right graph), an error is triggered, namely “ERROR 7100”. Each error is assigned to a particular flag value, which corresponds to a particular failure criterion. In this case, the air supply being cut-off would result in the combustion process being stopped. For a brief amount of time, the temperature would surge as the combustion mixture becomes fuel-rich and reaches a lower equivalence ratio. It was important to keep checking if the equivalence ratio is maintained as the inlet flow rates of the air and the fuel are very important to maintain the flameless combustion characteristics, essential for the efficiency of the system. It can be seen, as the air supply is cut-off, the temperatures suddenly rise (top-left graph). The temperature of the exhaust gas at the exhaust gas inlet of the recuperator must not exceed 750 °C, and hence, the controller automatically attempts to mitigate this by increasing the water injected into the system to cool down the exhaust gases (bottom-right graph,

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"green" curve). However, due to the persistence of the failure criterion, the controller switches into a safe operating state called the "EMERCENCY STOP". In this state, the controller switches off the fuel supply and the air supply completely, opens the pressure control valve completely to relieve the system from any built-up pressure inside, and opens the input channel to introduce Nitrogen (in a small quantity) into the system to extinguish the combustion flame. The system continues to stay in this safe operating mode, until the temperature and the pressure values of the system reach ambient conditions.

In Figure 13, the opening percentage of the pressure control valve was deliberately reduced, due to which the pressure in the system increased gradually. Beyond the maximum pressure limit of 8 bar, the system must switch into a safe operating mode and trigger an error. As seen in the figure (top-left), as the pressure limit exceeds the defined pressure limit, an error "ERROR 7000" is triggered (bottom-left in Figure 13). The controller responded by ramping up the opening of the pressure control valve to 100% gradually to avoid any pressure surges (as seen in bottom-right of Figure 13), thereby reducing the pressure level to ambient conditions with time. In this operating state, fuel supply is cut-off (top-right), and the air-supply to the CC is also cut-off. As mentioned above, the controller opens the input channel to introduce Nitrogen (in a small quantity) into the CC to extinguish the combustion flame.

In Figure 14, it can be seen that the temperature level at the outlet of the CC shows a sudden rise and increases beyond the defined operating level of 1200 °C. The failure was simulated by intentionally and momentarily decreasing the air intake into the CC, thereby reaching near-stoichiometric conditions of combustion. As the failure criterion persists, and the temperature level rises continuously, the error "ERROR 5000" is triggered (bottom-left in Figure 14), and the system reverts to a safe operating state. The controller responded by increasing the air supply and the quantity of water injection into the system (bottom-right in Figure 14) to cool-down the system more quickly and opening the pressure control valve by 100% to relieve the system of any built-up pressure. The controller shuts off the fuel supply to the CC (as shown in the top-right of Figure 14) and opening the input channel to introduce Nitrogen (in a small quantity) into the CC to extinguish the combustion flame.

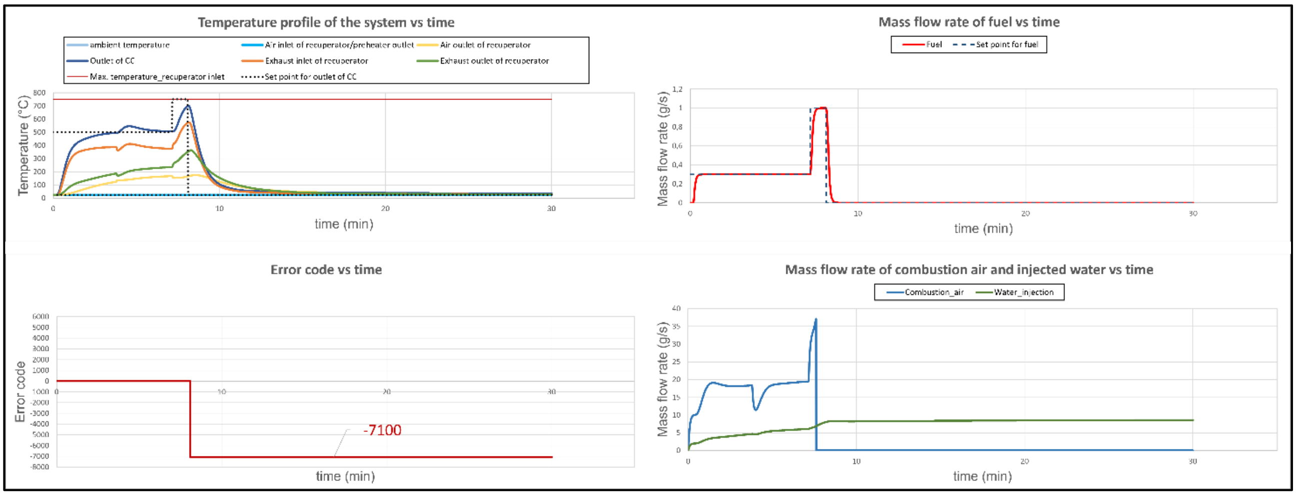

Figure 12: Failure occurrence due to switching off the air supply valve. (Air supply cut-off)

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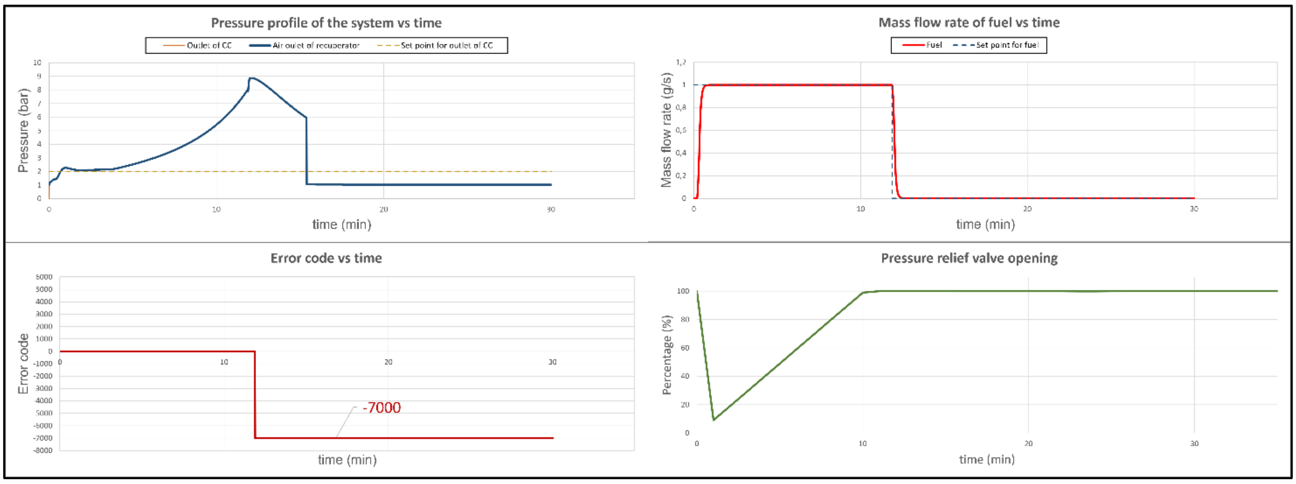

Figure 13: Failure occurrence due to switching off the pressure relief valve. (Pressure value at the outlet of CC exceeding the defined maximum value of the pressure limit).

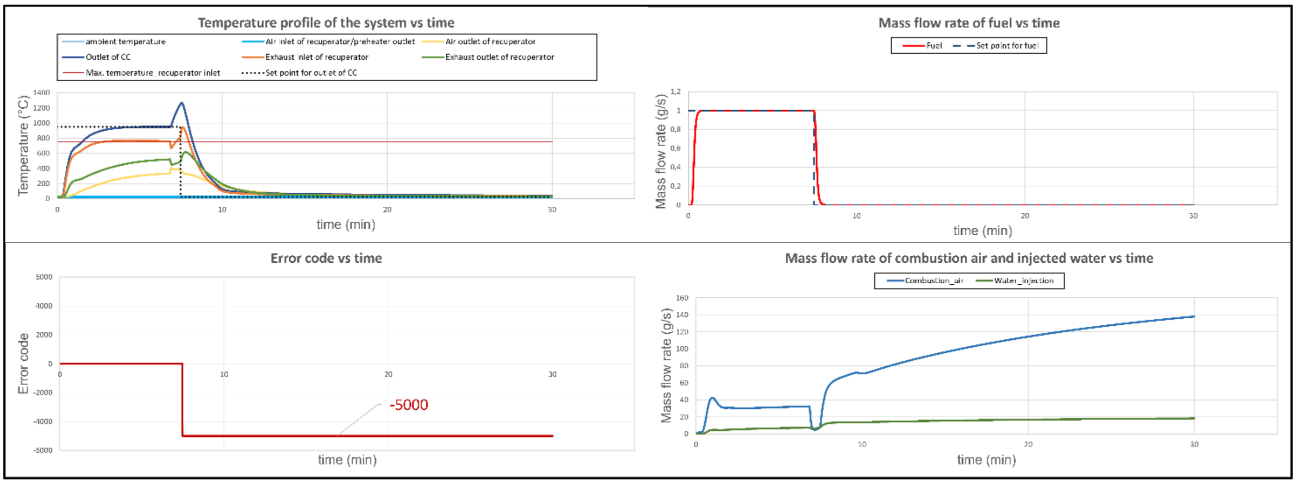

Figure 14: Failure occurrence due to the rise in the temperature-levels beyond the permitted maximum limit.

The failure occurrences mentioned in this section show only a few examples of how dynamic fault handling was incorporated into the control module. The complete list of the failure occurrences and their corresponding error codes is shown in Table 1 as follows.

Table 1: Table of list of error codes and the respective failure criteria.

Error Code	Failure criterion
0	No errors.
5000	If the temperature level outside the CC > 1250 °C. OR If the temperature level inside the CC > 1500 °C. OR If any thermocouples are damaged or disconnected.
7000	If pressure level in the system exceeds 8 bar.
7100	When the set-points for the controlled variables are changed (e.g. fuel flow, combustion air flow, atomization air flow) and their respective measured values

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	do not match their set-point values for more than 30 seconds, then this error signal is triggered.
7200	If the measured values of the controlled variables (e.g. fuel flow, combustion air flow, atomization air flow) exceed their predefined maximum limits respectively.
7300	If the measured values of the controlled variables (e.g. fuel flow, combustion air flow, atomization air flow) are less than their predefined minimum limits (in any operating state) respectively.
8000	If no flame is detected upon the start-up of the system (in any operating state) in the CC for more than 60 seconds, this error signal is triggered.

3.2. Hardware-in-the-loop testing of the controller with the virtual twin of the plant

As explained in the Section 3.1, the control algorithm is tested for all the operating states and failure criteria as required by the mGT operation guidelines. In the final step of testing called HiL, the SIMULINK model of the control algorithm with the virtual plant was extracted into a compatible code, and then deployed inside the target controller, i.e. NI-CompactRIO as shown in Figure 6.

The NI-CompactRIO consisted of a controller CPU, and peripheral I/O modules to communicate with the sensors and actuators. The Inputs and Outputs of the controller were configured by programing the FPGA (Field programmable gate array) using the NI-LabVIEW FPGA. Hence, the interfaces of communication for all the sensors and actuators of the plant were configured and tested (on the real hardware controller). A LabVIEW main program was developed, which could run on the target controller directly, and the LabVIEW program was responsible for reading and writing the values for all the sensors and actuators in real-time (through NI-LabVIEW Real-time), respectively. Moreover, the main program was responsible for establishing the communication between the different parts of the control system toolchain (as shown in the Figure 15), i.e. the user-interface (also programmed in LabVIEW, shown in Figure 16, Figure 17, and Figure 18), the data acquisition program, the SIMULINK extracted and deployed test bench virtual twin in the controller CPU, and the secure server where the data was being transmitted to in regular intervals. Model Interface Toolkit (MIT) from NI-LabVIEW add-on packages was used to establish the communication between the SIMULINK extracted virtual twin of the test bench and the other parts of the LabVIEW main program [6]. The overview of the communication as an image is shown in the Figure 15 below.

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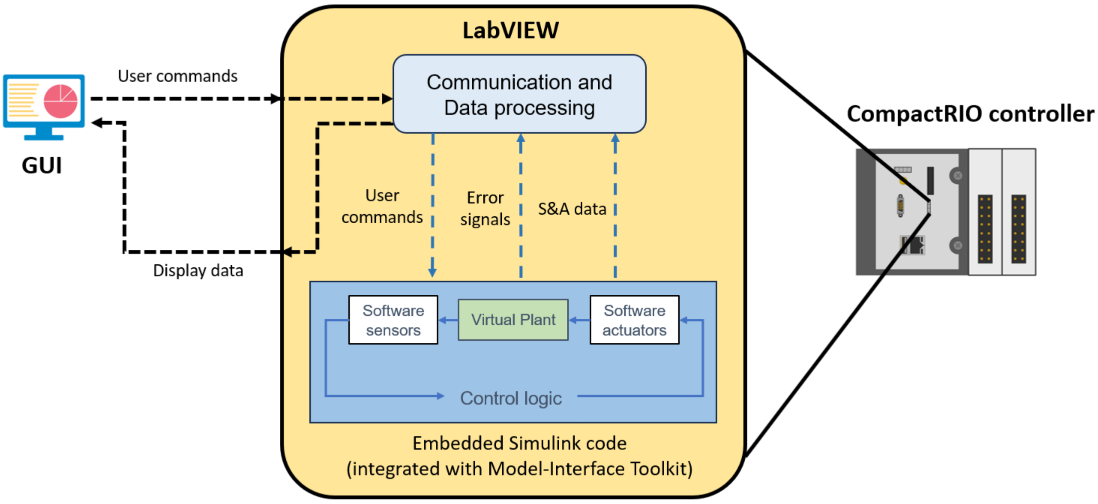

Figure 15: The communication between different systems of the controller toolchain for the Hardware-in-the-loop testing (HiL).

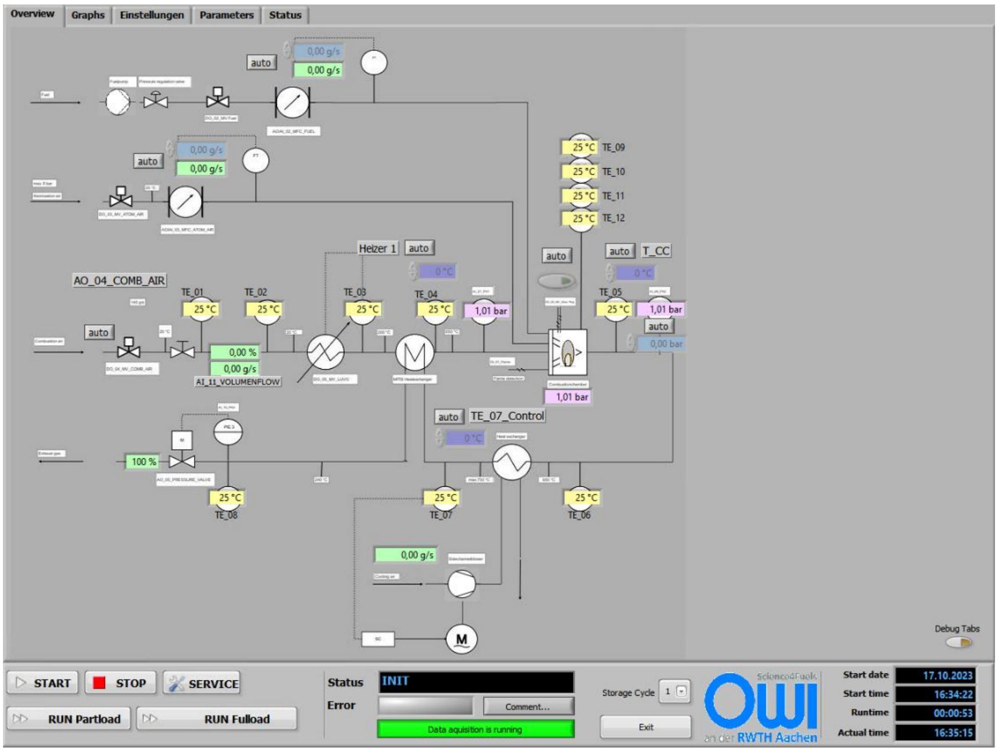

Figure 16: Control tab of the GUI.

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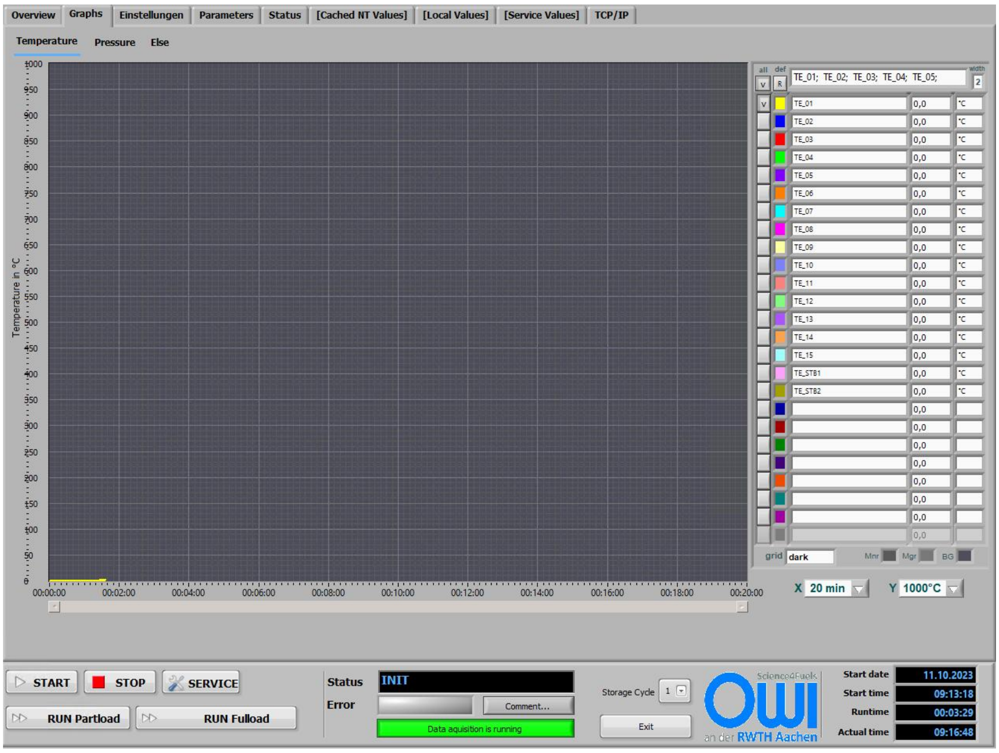

Figure 17: Data visualization tab of the GUI.

Figure 18: Configuration tab of the GUI.

Thus, it was made possible to test the control algorithm with the virtual twin of the plant in the hardware controller. The main advantage of this method was to test the functionality and the performance of the hardware controller without the need for an actual hardware plant. The real-time control capability of

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the controller was also validated. The controller was able to run the complete cycle, i.e. reading data from all the sensors, processing the data with the help of the control algorithm and updating the actuator signal values under 100 milliseconds.

3.2.1. Validation of the Hardware-in-the-loop results

The tests conducted at the SiL level formed a validation data set for further tests. Tests under the same conditions were conducted also at the HiL level to ensure that the hardware controller was able to carry out all its functions in real-time.

The test results were compared to the behavior of the controller in the earlier lower-level tests, and it was confirmed that the hardware controller was able to execute the deployed control algorithm flawlessly, the complete control cycle was executed in real-time, and the communication between the different parts of the control system toolchain was seamless.

In Figure 19, it is shown how the temperature profile of the system under the same operating conditions showed the same dynamic behavior of the system for the SiL-tests and the HiL-tests. Through iterative testing, the complete functionality and the performance of the control system, including the user-interface, the data-acquisition system and the control algorithm running inside the hardware controller were tested.

- Test results for the SiL and HiL align

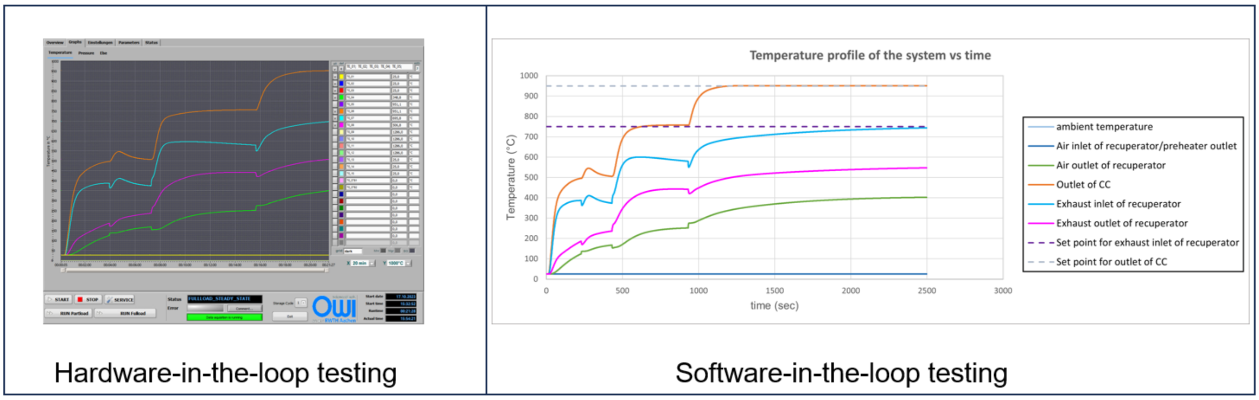

Figure 19: The validation of the test results for the HiL-level from the data set of the results from the SiL-level.

3.3. Controller development for the practical application and testing with the actual plant

The commissioning of the actual test bench involves testing the controller and fine-tuning the controller parameters to suit the dynamic behavior of the actual plant. Due to iterative testing at the SiL and the HiL levels, the controller was already developed for such a robust practical application. However, with respect to the actual micro-gas turbine plant, optimal control parameters can be found out through further hardware testing.

The controller development for the testing with an actual micro-gas turbine was also undertaken, and due to the architecture consisting of isolation between the hardware controller and the deployed control algorithm, the controller preparation for the actual testing was made to be very feasible.

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As shown in Figure 20 below, instead of deploying the extracted SIMULINK code of the complete test bench, including the virtual twin models of the plant system and the controller system interconnected together (top), just the virtual controller model (SIMULINK) was extracted and deployed in the hardware controller (bottom). In the LabVIEW main program, an extension of the program assigned the data from actual sensors to the input of this deployed controller model and assigned the output of the deployed controller model to the correct actuators.

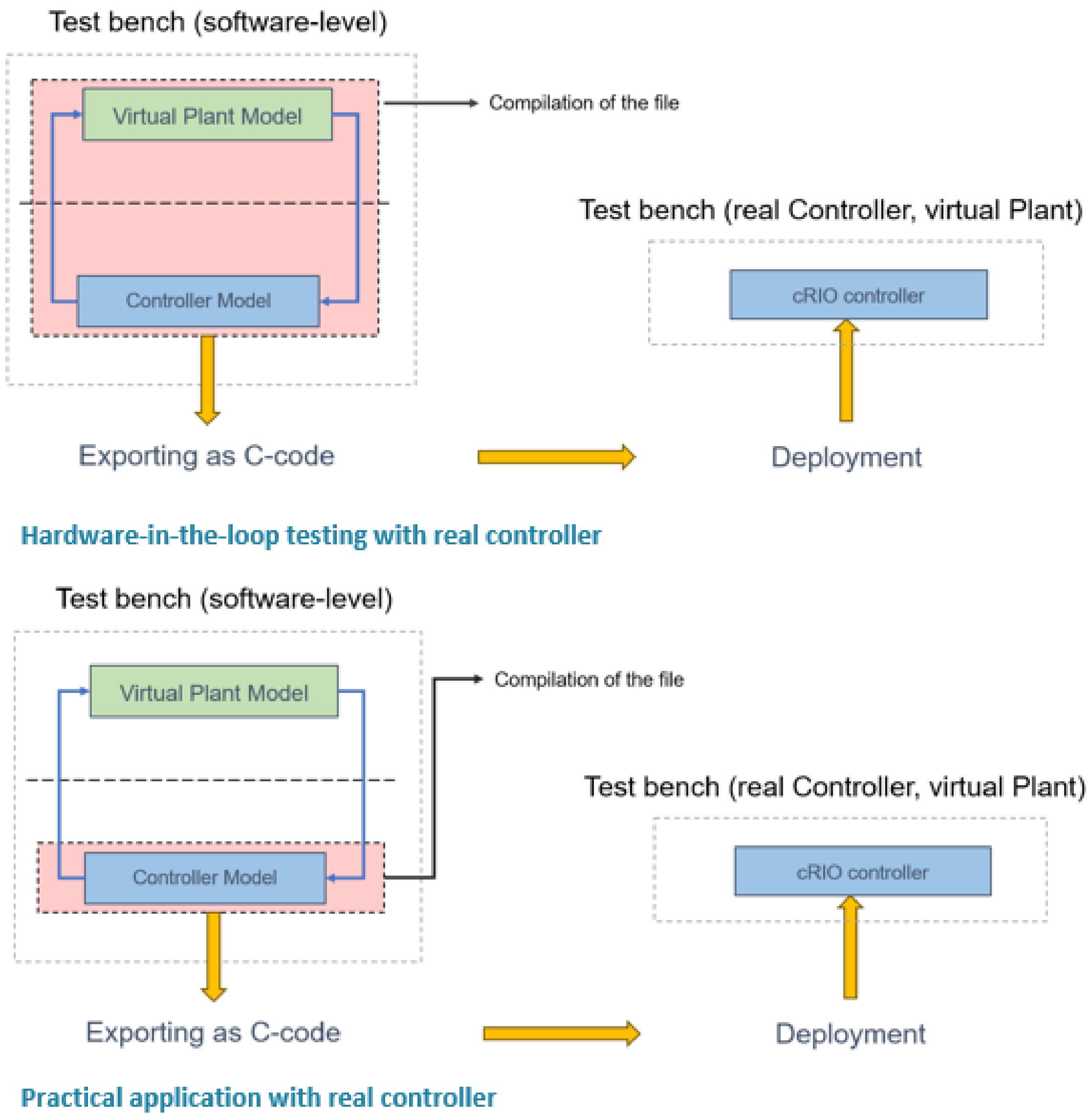

Figure 20: Controller development for the a) HiL testing (top) b) practical application with an actual plant (bottom).

Hence, the controller development for the practical application was also achieved in the scope of the section.

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4. Conclusions

A robust working controller was developed through a systematic and structured procedure. The hardware-in-the-loop testing of the controller was the final testing stage before its deployment with the actual hardware mGT plant. The controller development as well as testing was carried out in parallel to the hardware development and commissioning of the actual mGT system. The main benefit of the selected approach was the reduction of costs in the development, testing and commissioning phases for the mGT system. A robust controller was developed, tailored to the user and system specifications and operation guidelines, without the need for an actual plant.

The demands that were to be addressed in the development of the controller were, 1) studying the interfaces needed for the sensor/actuator signals in compliance with the hardware, 2) considering the dynamic behavior of the sensor signals and the plant system, similar to the actual hardware plant, 3) real-time capability, and 4) development of the model code on the same platform as the system control. During the development of the virtual twin models of the plant and the controller in SIMULINK, the sensor and actuator signals were considered as non-linear signals, including noise and delays. Thus, the control algorithm was expected to perform under dynamic, varying sensor and actuator signals. Later during the HiL testing phase, the sensor and actuator interfaces on the peripheral modules of the hardware controller were configured and hardware tests were conducted to see if all the real sensors and actuators communicated as expected with the hardware controller. The dynamic behavior of the real mGT system was modelled by creating and interconnecting all the individual sub-components in SIMULINK, exactly how it is in the real mGT system. The cascaded SIMULINK grey-box models included in the virtual twin of the plant consisted of data and properties from different fluids and solid materials, mathematical models, empirical models, as well as chemical reaction models to realize the dynamic behavior of the real mGT plant within a certain range of accuracy. Similarly, the complex control algorithm allowed flexible operation of the mGT in different operating modes, while also compensating for disturbances and fault-handling. The robust control algorithm was later also deployed and run in the hardware controller (NI-CompactRIO), to check for the real-time capability. The NI-CompactRIO controller was developed to provide flexible, robust and real-time control.

The NI-CompactRIO controller was developed for practical application, but the real dynamic behavior of the actual mGT plant can vary from the virtual twin model of the plant. The iterative testing at different hierarchical levels of the controller development procedure resulted in development of a fast, robust and flexible control system but the control parameters must still be manually entered and fine-tuned by the user. For the optimal controller performance, the developed controller must also be tested together with the real mGT plant. However, the HiL testing has already saved a huge amount of time and reduced the costs substantially for the initial commissioning tests, as they were already conducted without the need for the hardware components of the plant.

The future scope of work should consider testing the currently developed hardware controller together with the real mGT, to further fine-tune the performance of the controller in different operating modes, especially for the two-staged micro-gas turbine using liquid fuel as the energy source and operating in low as well as high pressure ranges.

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