

Novel Hardware-in-the-loop Approach for Thermal Systems

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Abstract

Hardware-in-the-Loop is a method that allows real-time testing of complex systems. A physical system can be analyzed using a programmable logic controller and simulation-based periphery. In this paper, a Hardware-in-the-Loop system using a LabVIEW-controlled thermal test bench as well as a MATLAB simulation is presented. The LabVIEW program is able to take over the communication with the physical system and the simulation. The discrete time steps between each simulation call and test bench control are to be minimized to allow a near-continuous operation and control of the physical system. A heat pump-based domestic heating system was tested to analyze this approach. The test bench controls the volume flows and temperatures according to the current demand for space heating and domestic hot water from the simulation. By applying this software-based approach, no external programmable logic controllers are necessary for the realistic testing of thermal systems and, therefore, extend the applicability of the Hardware-in-the-Loop testing approach.

Keywords: Hardware-in-the-loop, software-based approach, thermal test bench, heat pump system

1. Introduction

Determining the realistic outcome of a specified hardware design or application can be complex and difficult without proper testing. The Hardware-in-the-Loop (HiL) approach utilizes real-time signals from a controller to communicate with a physical sub-system as if it is in a real system. Through the use of HiL, comprehensive, reliable, and scalable tests of a hardware component of sub-system are possible without the need of using a fully assembled system. HiL is used in a multitude of engineering applications (Nabi et al., 2004; Snider et al., 2022). One example is the investigation of domestic heating systems (Stutterecker et al., 2015).

In (El-Baz et al., 2018), a HiL system is being used to investigate a heating system consisting of a heat pump, thermal storage and a building. While the heat pump and storage are within a thermal test bench, the behavior of the building is being calculated within a simulation model. The communication between simulation model and testbench is implemented using an external programmable logic controller (PLC). Also, in (Nürnberg et al., 2017) thermal test bench setup is introduced, which is able to determine the performance of heat pump systems using HiL. The heat pump is installed within a thermal test bench, while the building is being simulated. As in a previous investigation, the communication is established using a PLC to combine the two worlds.

A PLC offers the possibility to physically separate the machine where the simulation is performed and where the communication is realized. This can be beneficial while dealing with complex simulations which are time consuming and therefore need to be run on a high-performance machine to calculate the system behavior in real-time. Since the simulation complexity can be reduced for some investigations, the physical separation of machine and simulation running device is not needed, therefore use of a PLC can be avoided by running communication and simulation on the same machine. By that, complexity and effort to setup a HiL-based investigation can be reduced. Also, laboratories or users that do not possess an external PLC can use the HiL approach presented for their experiments.

In this paper, a HiL approach that does not require a PLC is introduced by combining a LabVIEW controller with a MATLAB Simulink simulation. LabVIEW is a graphical programming environment for testing and measuring (National Instruments, n.d.) for different engineering applications. MATLAB Simulink is a

graphical environment used to design and simulate systems (MathWorks, n.d.). By combining the LABVIEW controller directly with a MATLAB simulation, the PLC unit can be avoided implicitly. A disadvantage of this approach is that the communication between the hardware and software is not continuous anymore but communicates discretely in certain time steps. Minimizing the time steps between each model execution can reduce the difference between the usual continuous HiL approach with an external PLC and the introduced discrete HiL approach. Furthermore, this disadvantage can be negligible for rather inert systems such as domestic heating systems. The introduced HiL approach was implemented and tested at the thermal testbench of the Institute for New Energy Systems (InES) at Technische Hochschule Ingolstadt (THI). A heat pump (HP)-based domestic heating system was investigated. Thus, a first the proof-of-concept of the novel HiL approach without a PLC is provided in this paper.

2. Setup of the exemplary system

2.1. System overview and communication structure

A simplified setup was used to show the functionality of the novel HiL approach. For that, the example of a ground source HP is used for either space heating (SH) or charging a domestic hot water (DHW) storage. Within this experiment the switching of the HP operation mode between SH and DHW will be investigated. Fig. 1 illustrates the setup of the HiL system.

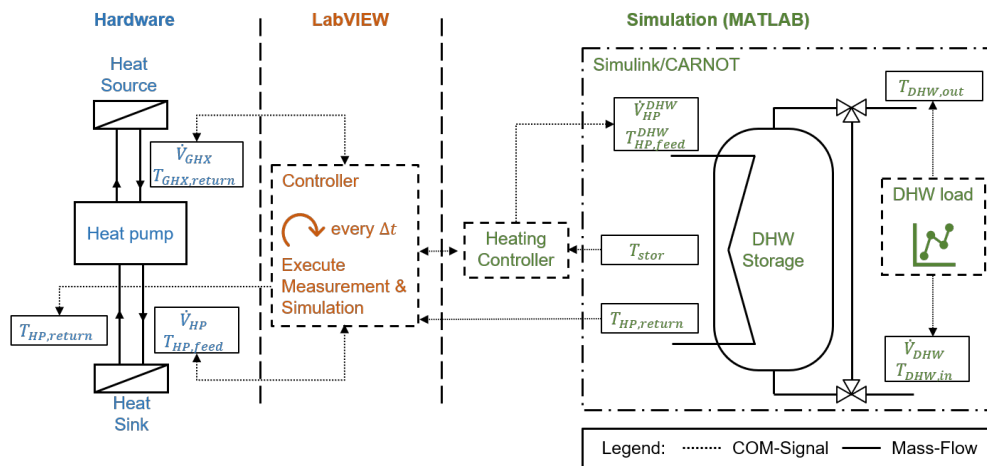


Fig. 1: Schematic drawing of the exemplarily investigated Hardware-in-the-Loop system

On the left side in blue the installation of the HP within the thermal test bench is shown. The test bench provides multiple hydraulic cycles acting as heat source or heat sink. The HP is connected with both a heat source and a heat sink via isolated pipes. The insulated pipes connecting the heat pump to the thermal test bench led to small delays in the control loop. This can be detected in the measurement results and influences the speed of the PID controller. The overall methodology is not impacted. Each hydraulic cycle includes pumps and valves to control its return temperature and volume flow. The heat source acts as a ground source heat exchanger (GHX) which is kept at a constant operation point during the investigation. It contains brine, a water-glycol mixture, to prevent freezing at realistic ground source heat exchanger temperatures. The heat sink is filled with water as it would be in a real domestic heating system. The operation mode of the heat sink is switched between the DHW and the SH mode. When in SH-mode, the heat sink operation is kept at constant values. When in DHW-mode the setpoints are received from a simulation model. This is implemented by specifying the setpoints for inlet and outlet temperatures $T_{HP,return}$, $T_{HP,feed}$ and the volume-flow \dot{V}_{HP} .

The control of the test bench components and the communication between hardware and simulation model is implemented in LabVIEW. The control of the test bench is implemented using PID controllers. By that, a setpoint can be specified inside the LabVIEW program and the operation point of pumps and valves are set to reach the setpoints. The control loop is executed at a fixed time-step Δt . As mentioned, the setpoints are calculated inside a simulation when the HP is in DHW-mode. For that, the measured values \dot{V}_{HP} and $T_{HP,feed}$ are used to initialize the simulation model of the DHW storage. After initialization, the simulation model is

executed and simulated for the same Δt at which the control loop is iterated. As long as the calculation time of the simulation is smaller than Δt , the setpoints for the test bench are updated in real time. As already mentioned in the beginning, this is a limit of this approach which needs to be investigated in further experiments.

On the right side of the figure in green, the components inside the simulation model are shown. In the given case, the heating controller which determines the HP's operation mode is implemented within the MATLAB environment. This could also be done within LabVIEW. The behaviour of the DHW storage is modelled in the MATLAB Simulink environment using the CARNOT Toolbox (Solar-Institut Juelich, 2022). Whenever the HP charges the DHW storage, the heating controller sets the volume flow to the corresponding value \dot{V}_{HP}^{DHW} and initializes the simulation together with $T_{HP,feed}^{DHW}$ from the test bench. Within the simulation the return temperature $T_{HP,return}^{DHW}$ after one time step Δt is calculated and fed back to the controller in LabVIEW. An exemplary DHW load profile is used to simulate the discharging of the DHW storage by setting the values for the tapping \dot{V}_{DHW} , T_{FW} , and T_{DHW} within the simulation model.

2.2. Heating controller

As described, the heating controller switches the operation mode of the investigated HP by changing the setpoints of the heat sink of the test bench. Therefore, the volume flow and the return temperature need to be determined for both charge and discharge modes. The heating controller reads the storage temperature at 50% height (T_{stor} in Fig.1). Depending on the value of T_{stor} , it changes the operation mode. When the temperature T_{stor} drops below a lower limit $T_{lim,low}$, the HP's operation is changed to DHW-mode. DHW preparation is commonly prioritized over SH operation (EVERGREEN ENERGY LTD., n.d.). The latter is a slow process due to the thermal inertia of heating systems. It remains in the DHW-mode until the storage temperature reaches an upper limit of $T_{lim,high}$. In every other case the HP is in SH-mode. Following this logic, the volume flow of the heat sink can be determined by the following equation:

$$\dot{V}_{HP} = \begin{cases} \dot{V}_{HP}^{DHW} & \text{if } T_{stor} \leq T_{lim,low} \text{ or } (\dot{V}_{HP} = 500 \text{ and } T_{stor} \leq T_{lim,high}) \\ \dot{V}_{HP}^{SH} & \text{otherwise} \end{cases} \quad (\text{eq. 1})$$

The return temperature is determined in the same way, while the setpoint during SH-mode is constant and during DHW-mode is being calculated within the simulation model and updated at each iteration.

2.3. Used system parameters

For the given investigation several parameters were specified to simulate a realistic scenario. Table 1 provides the system and simulation parameters.

Tab. 1: Specified Parameters within the investigation

Description	Value	Units
Inverter frequency level	75	%
Setpoint volume flow of heat source	$\dot{V}_{GHX} = 1250$	l/min
Setpoint temperature of heat source	$T_{GHX,return} = 10$	°C
Setpoint volume flow of heat sink	$\dot{V}_{HP}^{DHW} = 600$ $\dot{V}_{HP}^{SH} = 900$	l/min
Setpoint temperature of heat sink	$T_{HP,return}^{DHW} = f(sim)$ $T_{HP,return}^{SH} = 30$	l/min
Initial storage temperatures	40 – 45	°C
Volume of DHW storage	200	liter
Lower limit storage temperature	$T_{lim,low} = 40$	°C
Upper limit storage temperature	$T_{lim,high} = 45$	°C
Time step	$\Delta t = 2$	s

The HP used works as an inverter-driven brine source HP. The inverter frequency is set to 75 % relative speed for the duration of the experiment. Volume flow and return temperature of the heat source are kept constant at 1250 l/min and 10 °C respectively. Volume flow as well as return temperature of the heat sink vary according to the state changing between SH and DHW mode. The lower limit for the heating mode was set to 40 °C while the upper limit was set to 45 °C. The simulation model of the DHW storage is a 1D-model using 10 layers. The storage layers are initialized at a temperature between 40 to 45 °C. This represents a nearly fully charged DHW storage at the beginning of the investigation. The volume of the DHW storage has been set to a typical volume of a single-family house of 200 liters. With a time-step Δt of 2s, the simulation was consistently completed before the next iteration of the LabVIEW program took place.

3. Results

In this paper, the DHW mass flow, storage temperatures, and the temperatures of feed and return flow are analyzed in order to determine if the heat storage controller and model properly is communicating with the thermal test bench. This communication is essential to evaluate if using LabVIEW and MATLAB can be used together in a HiL setup for thermal systems. The LabVIEW testbench runs the thermal HP in a general day to day setting with the DHW storage being utilized throughout the day for various tasks such as showering, washing hands, dishes, or doing laundry. Whenever the DHW storage is used, the mass flow increases and tapping occurs until the task is completed. The task depends on the value of the DHW mass flow with more intense tasks requiring a larger mass flow (for example, filling a bathtub).

For this investigation the time period from 07:00 a.m. until 09:00 a.m. was chosen, when several and different quantities of DHW are tapped. In Fig. 2 the DHW mass flow, storage temperature and feed and return flow temperatures of the heat sink are displayed.

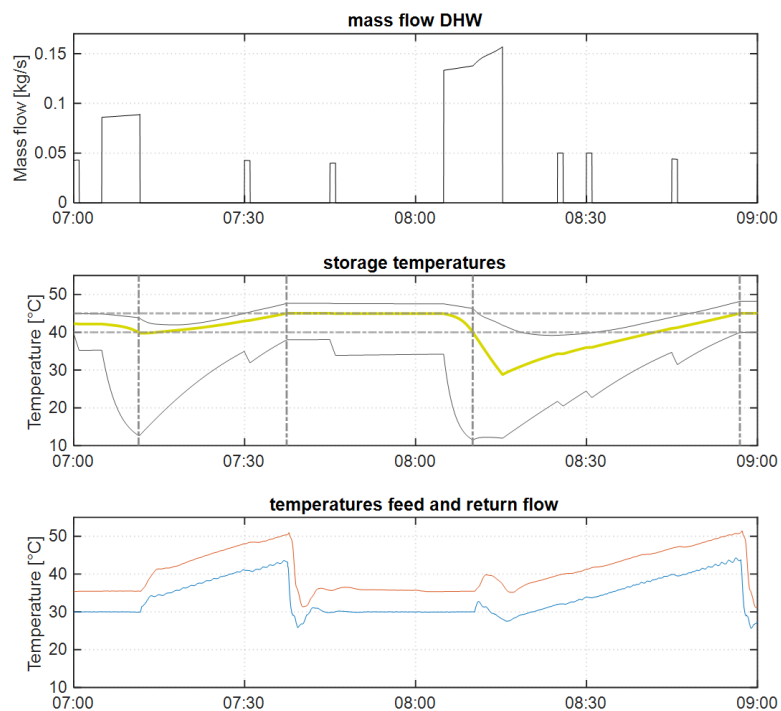


Fig. 2: DHW massflow, storage temperature, and heat sink's feed and return flow during the investigated time period from 07:00 a.m. until 09:00 a.m.

The x-axis represents the actual time within the day that the HP was running within the thermal system, starting at 07:00 and ending at 09:00. The first plot of DHW mass flow depicts this when the DHW storage is being utilized for various tasks within the two-hour run time of the HiL system. Below the simulated storage temperatures at top, middle and bottom are plotted. The green line refers to the temperature in the middle at 50 % storage height, which the heating controller uses as input to determine whether the HP is in DHW or SH mode. The horizontal dotted grey lines represent the limits of the heating controller as mentioned above. The

vertical dotted lines indicate the switching points when the HP switches its operation mode. The bottom plot displays the feed and return temperatures of the heat sink which were measured at the test bench.

At the beginning of the measurement a small tapping occurs. Due to the small quantity, this tapping lowers only the lower storage temperatures and doesn't lead to a switch of the HP's operation mode. Therefore, the HP stays in SH-mode which can be seen in the lower graph, where the feed and return temperature are stable at 35 °C and 30 °C respectively. During the first large tapping cycle occurring around 07:05, the water in the DHW storage decreases, and as expected the temperature of the storage levels decrease. Once the storage temperature at 50 % height reaches the lower threshold temperature, the HP goes into DHW mode. When in DHW mode the thermal test bench quickly increases the temperature of the return flow by about 5 °C, then increasing continuously. This is a result from the heat storage simulation and lets the HP feed temperature increase accordingly. At around 07:30 a small tapping occurs which slows down the charging process of the storage. It leads to a reduction in the lower storage temperatures and therefore, to a lower return flow temperature. At around 07:40 the storage is recharged again and the storage temperature at 50 % height reaches the upper threshold. As a consequence, the HP switches back to SH mode. This switch can be again identified also in the lower graph, where the feed and return temperatures switch back to their initial constant values at the beginning of the measurement. When switching back, the temperatures of feed and return flow take about 5 minutes until the values become stable again. The delay is caused by the parametrization of the PID-controllers for the volume and temperature control of the heat sink. This can be improved in the future by redefine the PID parameters and therefore improve the response of the test bench. Conclusively, this delay is not a consequence of the described HiL approach.

From 7:40 until 08:05 only a small tapping occurs, which lowers again only the lower storage temperatures. The next tapping occurs at around 08:05 and is the largest quantity during the whole investigation. During this tapping cycle, the temperature of the DHW storage levels decrease at a faster rate due to the higher DHW mass flow. This leads again to the HP going into DHW-mode at 08:12 before the tapping is completed as can be seen from the third vertical dash-dotted line. Although the HP is in charge mode, the storage temperatures continue to decrease as the HP power is not large enough. However, when the tapping stops at 08:15, the storage is being charged until the upper threshold storage temperature is reached as expected at the fourth vertical line.

During the phase from 08:10 until 8:15, when the storage is charging while tapping occurs, the storage temperatures continue to decrease. This can be seen more detailed in Fig. 3. There, the feed and return flow temperatures and the thermal storage temperatures are displayed during the second large tapping cycle.

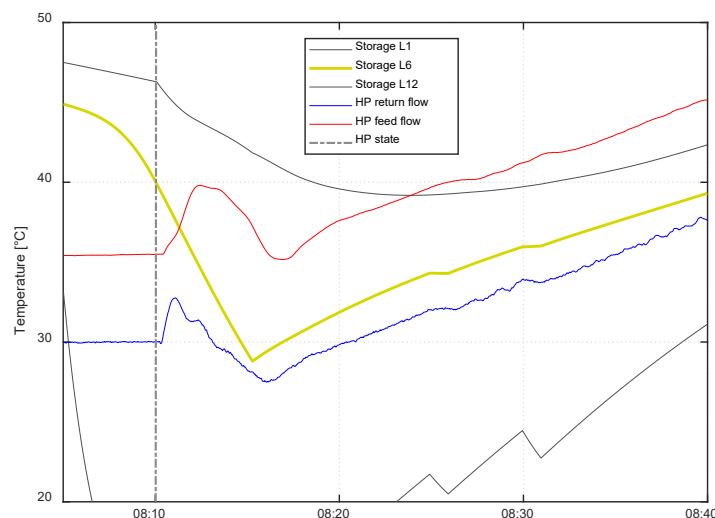


Fig. 3: Feed and Return flow output temperature with storage temperatures during the third switching point

The storage temperature at the top (upper grey line) is still decreasing until it crosses the HP's feed flow (red line) at around 08:24. The reason behind that is the mentioned temperature difference between feed and return flow which is for the investigated HP constantly around 7 °C. Since the return flow (blue line) at the end of

the tapping cycle is around 29 °C the feed flow temperature is at around 36 °C. Due to this fact, the feed flow temperature is lower than the storage temperature at the top from 08:10 until 08:24. This effect cools down the upper storage temperatures additionally to the DHW tapping. The main reason for this effect is the positioning of the heat exchanger inside the thermal storage and may not be the case in well-designed heating systems. Nevertheless, the fact that the results are can be reasonably explained conclude that the novel HiL approach is working as expected and can be used for further investigations.

4. Conclusion

This paper demonstrated a HiL system operating without a PLC by using LabVIEW as the communication interface between the thermal testbench and simulation system. To demonstrate the functionality of this approach, a physical HP and a simulated DHW storage were utilized. With this HiL approach, the heating controller reacted properly to the inputs and switched in and out of the DHW charging mode according to the simulated storage temperatures. Likewise, the test bench reacted to the simulation outputs and varied the return temperature and volume flow into the heat pump to demonstrate the different operation modes of SH and DHW preparation. The results matched the expectations.

Several interesting observations could be made during this switching process. During the second larger tapping, the response of the heat pump of not being able to cover the DHW tapping power can be seen. Even though the HP is charging already, the temperature levels still decrease until the tapping ends and the HP charges the DHW storage. This is commonly seen in heating systems, where the HP power usually does not cover the maximum DHW tapping power, but the DHW storage acts as a buffer tank in between. The control delay within the first few minutes is most likely an issue with the PID controller of the test bench. The effects of small DHW tapping cycles being low on the overall storage temperature level and only affecting the lowest layers is a realistic observation.

The investigated HiL approach can allow further studies on both the heat pump behavior as well as the heating controller. The studies range from varying the heat exchanger position within the DHW storage tank over the adjustment of the limit storage temperatures as well as a more detailed look into the heat pump reacting to different operation modes. However, the outcome was only evaluated qualitatively. Even though the results matched the expectations of such a heating system, the approach should still be validated with a physical heating system in the future. Furthermore, the limits of the approach need to be investigated more detailed. One limit could be the restrictions in simulation complexity in comparison to the available computational resources. Using a software-based system with LabVIEW and MATLAB promises to become an alternative to conventional PLC-based HiL operation. In the future, a software-based system can be tested on less inert systems.

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