Using a Thermal Energy Storage to Provide Flexibility for Heat Pump Optimization Control with Rapid Control Prototyping and SG Ready Standard

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Abstract—The coupling of the heat and power sector is required as supply and demand in the German electricity mix drift further and further apart with a high percentage of renewable energy. Heat pumps in combination with thermal energy storage systems can be a useful way to couple the heat and power sectors. This paper presents a hardware-in-the-loop test bench for experimental investigation of optimized control strategies for heat pumps. 24-hour experiments are carried out to test whether the heat pump is able to serve optimized schedules generated by a MATLAB algorithm. The results show that the heat pump is capable of following the generated schedules, and the maximum deviation of the operational time between schedule and experiment is only 3%. Additionally, the system can serve the demand for space heating and DHW at any time.

Keywords—*Heat pump, Energy management, SG ready, Thermal energy storage, Control strategy, Optimization, hardware-in-the-loop*

I. INTRODUCTION

Like other countries in the world, Germany is eager to steer its energy system towards a predominant supply by renewable energy, and significant progress has been achieved, so far especially in the sector of electricity generation. Here, in 2013, the share of renewables was about 25%; in 2017, it had already reached 36% [1]. However, this tends to increase the volatile portion of the electricity mix in Germany resulting in enhanced phases with supply and demand drifting apart. The coupling of the heat and power sector has been identified to work around this obstacle. One of the potential technologies in this respect is the coupling of a photovoltaic (PV) unit with a heat pump (HP) accompanied by an energy storage system. The latter can either be represented by a battery or by thermal energy storage (TES). Since batteries are still costly and thermal energy storage systems are in many cases inherent to heat pump systems, this paper focusses on exploiting the potential of a TES first, leaving the battery as an option for topping up the achievements presented in the following.

Various studies have been carried out for the analysis of heat pumps in combination with TES. Both experimental and theoretical studies by different institutions focus on increasing system efficiency and sustainability by the implementation of a proper control algorithm for the heat pump. Cruz et al [2] developed a hardware-in-the-loop (HiL) test bench for heating systems, which can be used to test control strategies and evaluate performance of HVAC systems. Additionally, dynamic building behavior is connected to the HVAC system and is simulated with a Modelica building model in real time to test the system. In this respect, Cruz et al examined the control strategy of an air-to-water-heat-pump (AWHP) and the results show a better performance of the heat pump and lower power consumption. Fischer et al presented a control strategy using the SG ready standard for pooling 284 heat pumps [3]. The control strategy suggested in this paper tries to determine the set points for the heat pumps in the pool and to track them using a set-value for the power consumption of the heat pumps. The optimization control respects the variable day-ahead market price for electricity. The results show that the control parameters need to be adjusted continuously to avoid oscillation of the heat pump pool. Seifert et al [4] published a HiL method to assess practical data of heat pump and micro CHP performance. The aim of their efforts is the implementation of a generally applicable evaluation method for these systems. As a result, they present a procedure for calculating the seasonal performance factor of both CHP units and heat pumps by testing the units based on the demand profiles of a few typical days only.

This paper presents a hardware-in-the-loop (HiL) method suitable for testing control strategies for heat pumps in combination with a TES using the SG ready standard promoted by the German Federal Association of Heat Pumps (BWP) [5]. First, the test bench and its components and the optimization algorithm are described. Additionally, the demand profiles of the experiments are presented along with the PV profiles. This is followed by a presentation and discussion of the results. The paper closes with a conclusion and an outlook on future studies and necessary adjustments.

II. MATERIALS AND METHODS

A. Test bench and hardware components

A schematic of the test bench is illustrated in Fig. 1. The heat pump on the test bench is a brine-water heat pump providing thermal power of 17.2 kW at B0/W35 and a maximum supply temperature of 65°C. The heat pump is equipped with two supply feeds, one for serving the heating system and one for preparing DHW. Accordingly, the TES with a total volume of 600 liters comprises two zones; an

upper zone for DHW (350 liters) and a lower zone for heating purposes (250 liters). The two zones are separated by a perforated plate allowing a limited exchange of water as the heating fluid. As the heat pump has only one inlet for the return flow, two electric valves are installed in the return flow of the heating and the DHW zones to enable loading the zones of the TES separately. For evaluation of the temperature distribution in the TES, 10 thermocouples are attached outside the tank evenly placed over its height.
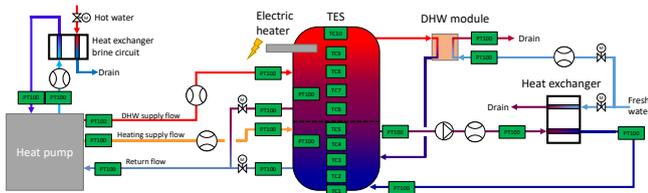

Fig. 1: Schematic of the test bench

To track the heat pump's operation, five PT100 sensors detect the temperatures in the supply and return flow of the heating and brine circuit. Additionally, the electric power of the heat pump is measured as well as the volume flow rates in the heating and the DHW circuit. The latter are needed for evaluation of the heat rates absorbed and supplied by the heat pump. In order to regenerate the brine circuit, hot water from the laboratory conduit is directed through a heat exchanger, for heating up the cold brine from the heat pump. A control valve guarantees a constant brine temperature by adjusting the flow of the hot water. The demand side of the test bench is represented by a heat exchanger and a controllable pump for the heating system and a DHW module. In the heating system, the supply is taken directly from the lower zone of the TES. The return temperature from the heat exchanger is kept constant by controlling the flow of the coolant. By a further PID control, the speed of the supply pump is adjusted to the desired heat rate supplied to the coolant. By this means, any profile with respect to heating demand can be applied. The DHW module operates in the same way to satisfy the DHW demand. Hot water from the upper zone of the TES is used to heat cold water from the fresh water conduit of the laboratory. A pneumatic control valve is installed for emulating the desired DHW demand profile. Corresponding to the heat pump circuits, PT100 sensors and flow meters are installed in the demand side circuits for evaluation of heat rates supplied to the heating system and the DHW module.

B. Scheduling of the heat pump

In order to find the optimum schedule for heat pump operation in combination with a PV unit and TES maintaining a maximum utilization of PV electricity for the heat pump, an algorithm has been implemented in MATLAB. The algorithm creates an optimal schedule for a period of 24 hours by a heuristic optimization method, and was originally developed and successfully applied to CHP units [6]. Meanwhile, this algorithm has been adapted to a system comprising heat pump, PV unit, TES for DHW and building mass as a thermal storage for heating [7]. As the TES of the system described so far is a two zone combined storage system for heating and DHW, the algorithm has been adjusted to fit this requirement.

C. Hardware-in-the-loop environment

As seen in Fig. 2, the output of the MATLAB function for optimization is a csv file containing the optimal schedule with control signals and information whether the heat pump should operate in heating or DHW mode. The control signals are based on the SG ready standard using the settings normal and forced operation only, as described in [5]. The csv-file is sent to LabVIEW, and a virtual instrument (VI) converts the schedule to a logical code, which is forwarded to a USB Box from National Instruments. The box receives the logical code and turns it to a 5 Volt signal, which is sent via digital outputs to the internal control of the heat pump. Regarding the demand side, the controls at the test bench described above maintain the desired heat rates for the heating system and for generation of DHW from the TES. LabVIEW collects all relevant data at the test-bench and processes it, for example temperatures at the TES or electric power consumption of the heat pump. In order to close the loop of the HiL environment, the temperatures of the TES are sent back to the MATLAB function. After 24 hours as the horizon for the scheduling, LabVIEW collects the data of the thermocouples at the TES and sends it via csv file to the MATLAB function. MATLAB processes the data and calculates the actual thermal capacity of the TES, which is used as input for the optimization of the schedule for the next 24-hour period.
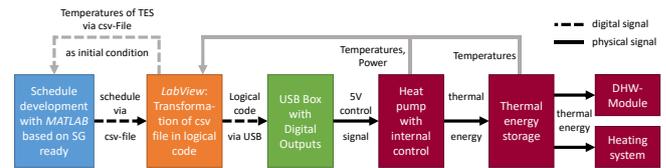

Fig. 2: Schematic of the hardware-in-the-loop environment

III. DEMAND AND PV PROFILES

The demand profiles are taken from the guideline 4655 of the Association of German Engineers (VDI) [8]. This guideline provides profiles for electricity, heating and DHW demand for 10 so-called typical days of the year in a resolution of one minute for single-family houses (SFH). The profiles can be scaled to actual yearly demands, and in this paper they are applied to a small apartment house with eight residents in Reutlingen, Germany (climate zone 6 in [8]) featuring a yearly demand for space heating of 40,000 kWh. According to [8], the yearly demand for DHW generation for a building occupied by eight persons is 4,000 kWh and the yearly electricity consumption is 12,000 kWh. Evidently, the heating system must be in accordance with the heat pump on the test bench, and for that reason a low temperature radiator system is assumed with a return temperature depending on outdoor temperature according to the heat curve of such a heating system. In order to carry out tests for the optimization algorithm, the different seasons of the year should be covered. For that reason, three typical days were selected from [8]: A day in winter, a day in summer and a day during the transition period representing either spring or fall. In detail, typical days WWB, ÜSH and SSX were selected. WWB represents a cloudy working day in winter, ÜSH is a sunny Sunday in the transition period and SSX is a summer

Sunday. Since the demand profiles for space heating from [8] are stochastic with respect to an on/off boiler, they were flattened by averaging for each hour of the day. In contrast, DHW and electricity demand profiles were applied directly with no further corrections. Fig. 3 shows the demand profiles for space heating (on the left) and DHW (on the right) for the three typical days selected. As the heat demand in summer is zero, the left diagram displays curves for the winter day and the day in the transition period only. As some of the DHW peaks, especially for days ÜSH and SSX, are too high for the test bench to handle, the tapping time was increased so that, together with the maximum power for DHW generation available on the test bench, the same amount of energy is transferred.
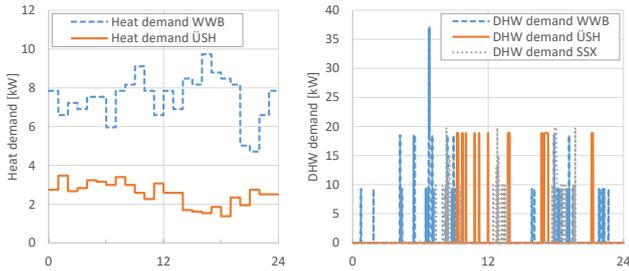

Fig. 3: Heat and DHW demand of the typical days WWB, ÜSH and SSX of [8]

The profile for PV electricity generation used in this paper is based on measured data from a PV plant near Stuttgart, Germany with a nominal power of 500 kW$_p$. In order to adjust PV power to the small apartment house in the sample case, the PV profile is scaled to a PV plant of 10 kW$_p$. Fig. 4 shows the PV generation profiles for a winter, summer and transition day.
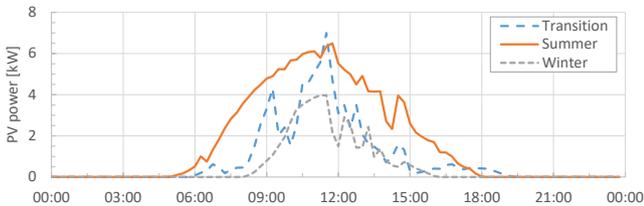

Fig. 4: PV profile for the examined typical days from measured data near Stuttgart

IV. RESULTS AND DISCUSSION

To prove whether the developed schedules of the MATLAB algorithm are applicable to real hardware, tests within the HiL environment described so far were carried out for the three typical days introduced above. The following section presents the results of these experiments. The discussion of the results is generally based on a diagram for visualization of the heat pump operation compared to the schedule (Fig. 5 to Fig. 7). In each diagram, the solid blue line (P_el_HP) refers to the measured electric power consumption of the heat pump during the 24-hour experiment and represents by this means the physical times of heat pump operation. The solid orange line (Schedule) represents the schedule imported from the MATLAB algorithm. The solid gray line (T_HW) illustrates the measured values of the temperature sensor in the heating zone of the TES, which is responsible for controlling the heat pump. The green dashed

line (T_HW_min) shows the set point for this temperature, which refers to the temperature for turning on the heat pump. Both temperatures are plotted on the secondary axis of the diagrams.

A. Winter day WWB

The results for the examined cloudy winter day can be seen in Fig. 5. It is evident that the heat pump is able to serve the developed schedule almost exactly. The schedule and the electrical consumption referring to the times of operation of the heat pump on the test bench overlap almost every time.
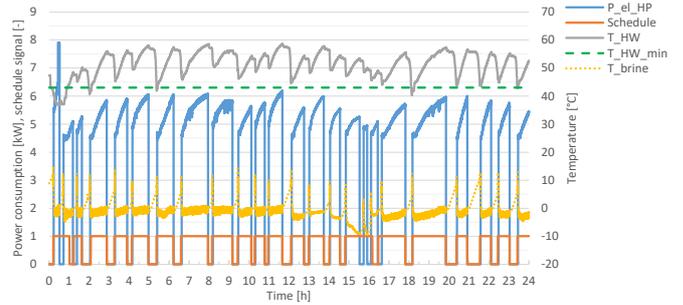

Fig. 5: Results of the experiment for the typical winter day WWB

The cumulated values over the entire period of 24 hours show that the deviation between the schedule and the actual running time of the heat pump is only 0.9%, as illustrated by TABLE I.

TABLE I: SUMMARY OF THE TEST RESULTS

Typical day	WWB	ÜSH	SSX
Time of operation test bench [min]	1,022	489	100
Time of operation schedule [min]	1,031	504	98
Deviation [%]	0.9	3.0	2.4

According to the schedule, the heat pump should run for 1,031 minutes during the entire day; on the test bench, the heat pump ran for 1,022 minutes. Only at the beginning of the day and around hour 16 was the heat pump not able to follow the schedule completely. As the heat pump needs to heat up the TES at the beginning of the experiment, which is done primarily in the DHW zone, the temperature in the heating zone T_HW drops under the minimum temperature T_HW_min, due to the heat demand at that time. After the temperatures in the DHW zone are sufficiently high, the heat pump switches into heating mode and charges the heating zone of the TES, which can be seen by the increase of temperature T_HW after 1 hour in Fig. 5. Since the supply temperatures for loading the DHW zone are higher compared to charging the heating zone, the compressor of the heat pump consumes more power. This explains the higher electric power consumption in the first hour. A drop of the brine temperature (T_brine, yellow dotted line in Fig. 5) under -10°C explains the violation of the schedule at hour 16. Whenever the brine temperature in the supply to the heat pump is too low, the heat pump will not turn on because of internal safety precautions. As the heat pump strives to serve the schedule, it starts to frequently switch between on and off mode, which can be seen between hour 15 and 16 in Fig. 5.

After the brine temperature was back to higher temperatures, the heat pump continued to follow the schedule. Despite the two deviations at the beginning of the experiment and at hour 16, the heat pump operation is in accordance with the optimized schedule from the MATLAB algorithm.

B. Transition day ÜSH

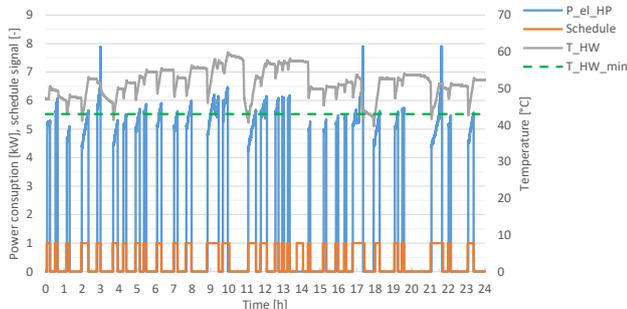The examination of the typical transition day with a clear sky is illustrated in Fig. 6.

Fig. 6: Results of the experiment for the typical transition day ÜSH

In this experiment, the heat pump was also able to serve the schedule quite well. The deviation between the scheduled time of operation for the entire day of 504 min and the actual running time on the test bench of 489 min is only 3%. Nevertheless, this deviation is a little higher compared to the results from the winter day, and the reason why can be seen at hour 14. At hour 14, the heat pump cannot follow the schedule because the TES temperature of 58°C in the heating zone T_HW is almost at its maximum and no capacity is left to operate the heat pump according to the schedule. Most likely, there was a deviation between the calculated capacity of the TES in the MATLAB algorithm and the actual capacity on the test bench.

C. Summer day SSX

Finally, the results for the summer day can be seen in Fig. 7. Unlike the winter and transition day, the demand profiles of the summer day start at 7:00 and not at 0:00, because long resting periods of the heat pump need to be avoided as the brine on the test bench heats up whenever the heat pump is not in operation. If the brine temperature rises above 18°C, the heat pump does not start due to internal safety precautions. Therefore, the examined day was started at 7:00 to avoid the long resting period during the night, since during summer there is no demand for space heating. As the heat pump only generates thermal energy for covering the DHW demand, there are not more than six starts of the heat pump during the day. Again, the heat pump can almost exactly serve the schedule, and the deviation between the scheduled time of operation and experiment is only 2.4%.
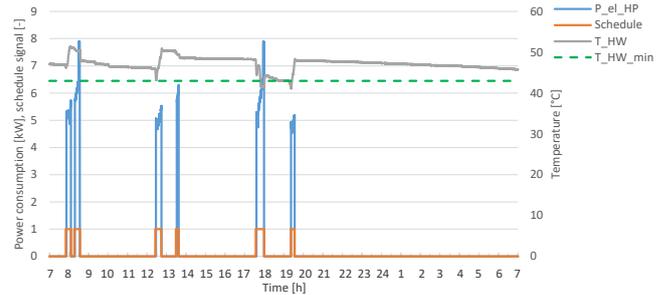
Fig. 7: Results of the experiment for the typical summer day SSX

V. CONCLUSION

The results of the 24-hour experiments show that the implemented HiL environment is capable of controlling the heat pump using an optimized schedule from a MATLAB algorithm to shift its operation in times of high PV generation. The deviations in operational time between schedule and experimental results on the test bench are small with a maximum of 3%. Hence, the goal of this paper to control the heat pump with an optimized schedule to maximize the PV electricity utilization is fulfilled. In addition, the system can serve the demand for space heating and DHW at any time. Further improvements of the system are the optimization of the calculation of the TES energy content in the MATLAB algorithm in order to achieve a better match to the behavior of the TES on the test bench. In this respect, it would be helpful to include the heat losses of the piping in the MATLAB algorithm.

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