DYNAMIC DESIGN AND VALIDATION OF SMART-GRID CAPABLE HEAT PUMP SYSTEMS IN RESIDENTIAL BUILDINGS

Kan, Chen, M.Sc., E.ON Energy Research Center RWTH Aachen, Mathieustr.30, Aachen, Germany;
Rita, Streblow, Dr. -Ing, E.ON Energy Research Center RWTH Aachen, Mathieustr.30, Aachen, Germany;
Dirk, Müller, Prof. Dr.-Ing., E.ON Energy Research Center RWTH Aachen, Mathieustr.10, Aachen, Germany;

Abstract: The research and evolution on smart home energy systems (HES) gains more and more relevance especially focusing on the reduction of carbon emissions, the optimization of the domestic energy efficiency as well as the improvement of indoor climate comfort. In this sense, heat pump (HP) systems are getting more and more relevance due to the efficient coupling with renewable energy source and higher CoP in comparison to other conventional HES. Future homes may install smart HP system for several reasons, including ambient assisted living, better comfort, optimized energy cost as well as the possible access to smart-grid technologies. In this work, a typical HP system as HES in a single-family house, which comprises an air-to-water HP and a domestic hot water storage tank, will be investigated. The main purpose of this work is to describe and propose a dynamic approach for design and validation of the smart-grid oriented HP systems in residential buildings.

Key Words: Design, Smart-Grid, Validation, Peak Reduction, Demand Response

1 INTRODUCTION

Future homes can support the integration of fluctuating renewable energy sources and help reducing CO2 emissions by applying active energy management (Fahangi 2010) and advanced heat generation processes like electrical HPs, gas HPs or combined heat and power generation units. A smart energy control on the thermal side as well as on the electrical grid side (Monti 2010) will be one of the key technologies to achieve these goals. Compared to a gas boiler system, advanced energy management and heat generation systems have more complex behaviors in terms of their transient performance and efficiency. Meanwhile the future HP control systems shall not only optimize the COP to decrease the primary energy demand, but also be smart-grid capable in order to optimize in a holistic manner accounting for the low and medium voltage grid load profiles.

Field studies including a large HP field study of E.ON Energy AG (Huchtemann 2011) in Germany have shown that the in-situ performance of complex heat generation units depends on the dynamic load conditions. Thus, standard steady state test procedures cannot predict the overall system performance of a standard HP system in detail. The performance of the HP systems depends on load fluctuations. Thus, dynamic test conditions have to be applied. On the one hand field studies of HPs allow a detailed study of the system performance, the user interaction and the acceptance of smart home technologies. On the other hand field studies always have to compromise accuracy and generality because every study is focused on a very limited number of building types and system solutions. Additionally, it is very difficult to optimize HP systems during a field study because of continuously changing and non-reproducible boundary conditions.

By using numerical simulation many configurations and parameter settings can be tested prior to the prototyping phase in order to reduce the time, operating effort and complexity. However, a precise simulation always requires detailed models as well as validation expenditures of the simulation models which are usually unavailable or hard to be analytically described what may reduce the validity of the results.

In order to use the advantages and to avoid the limitations of pure numerical simulation and field tests, the Hardware-in-the-Loop (HiL) approach can be applied as an intermediate step (Grosch 2008). Nowadays, the HiL approach is widely used during the rapid prototyping in different industrial fields e.g. power electronics (Majstorovic 2011), electrical drives (Steurer 2010) and control systems in automotive industries (Maclay 1997). The HiL testing applied in renewable energy technology, mainly focusing on wind turbines and fuel cells, has been reported in (Li 2006) and (Li 2010).

2 SYSTEM DESCRIPTION

The unique properties of the HiL tests can help also to examine the HP systems accounting for thermal, hydraulic as well as electrical behaviors. All essential parts of a HP system can be tested as real hardware. The missing parts of the system, e.g. the building, environmental energy sources and the grid connection will be emulated based on advanced simulation models and fast control equipment. It represents an innovative simulation and validation approach for HP systems where electrical and mechanical engineering questions can be solved at the same time.

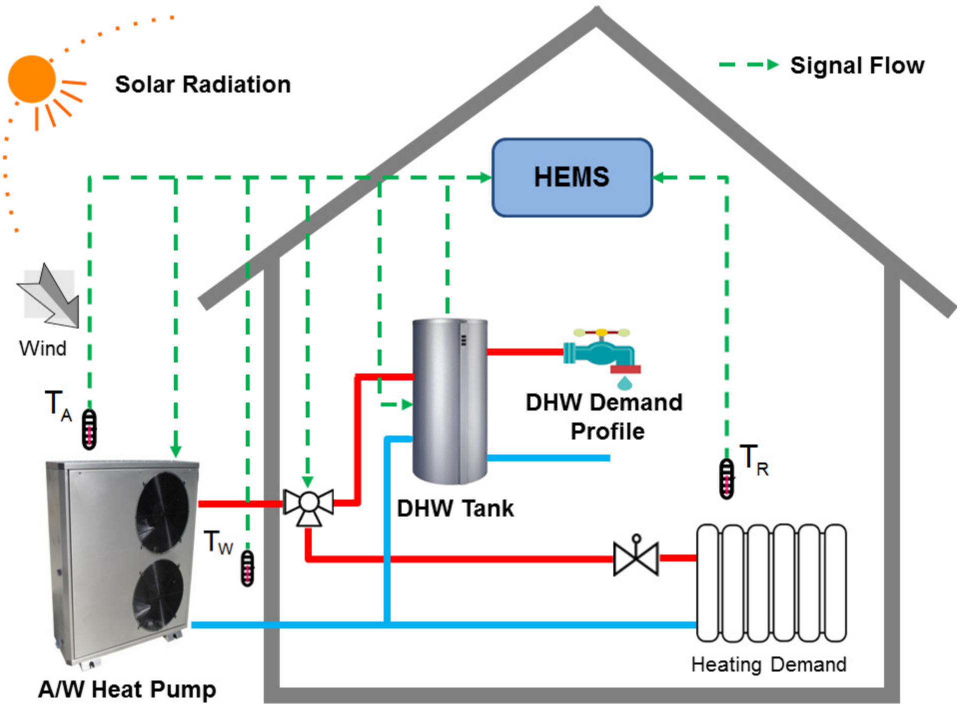

Figure 1: The Investigated Residential HP Installation

Figure 1 illustrates the installation scheme of an air-to-water HP system. The house is heated by a speed controlled HP which regulates the compressor power according to heat demand. The outlet water from the HP flows directly into the heating system e.g. radiator or floor heating of a single-family house and heats up the room temperatures. The DHW demand of the household such as hand washing or showering which is described by a load profile is covered by the DHW tank. The direction of the outlet water from the HP is switched by a three-way valve, which decides if the room or the tank should be heated up. The control and communication between the components are expected to be realized by the Home Energy Management System (HEMS). The HP including the DHW storage unit at the power level of the HiL setup is considered as Hardware-under-Test and the HEMS at the signal level is considered as Controller-under-Test in this work. The building model, the heat distribution system and the outdoor climate are treated as numeric models.

3 HIL-BASED DYNAMIC VALIDATION APPROACH

The principle of the HiL approach adopted in this work is depicted in Figure 2. It provides an effective platform by adding the complexity of the plant under control (real home energy components) to the test platform instead of numerical models, so that modelling errors and uncertainties can be reduced dramatically.

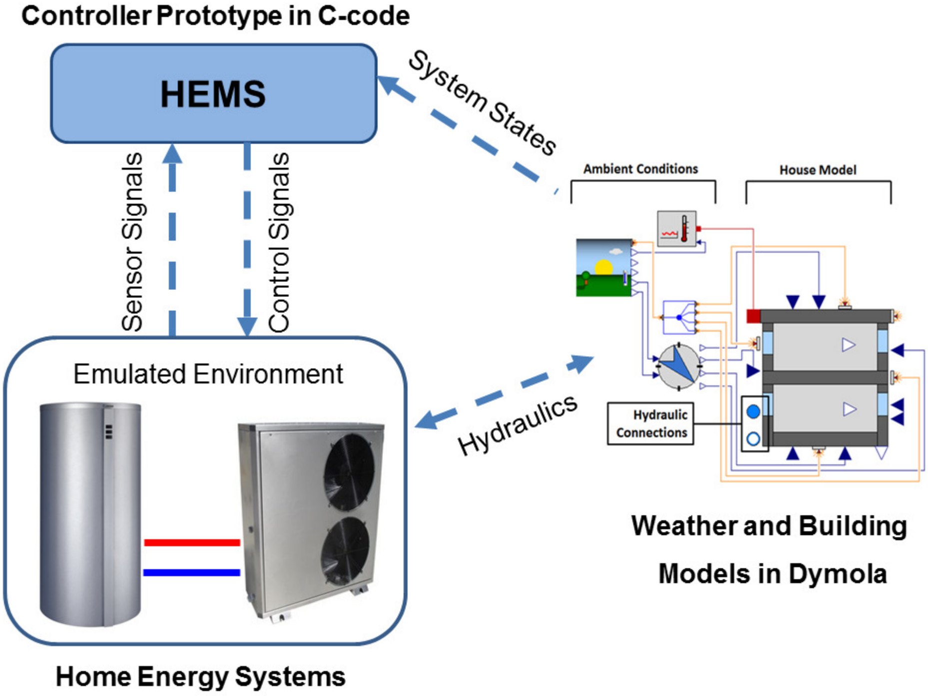

Figure 2: Principle of the HiL Approach for HP Systems

In order to keep the flexibility of the HiL simulation, the only numerical parts remaining in the loop are the weather and building models including the hydraulic systems in object-oriented programming language Dymola/Modelica, which can be modified and parameterized easily. Since the performance of the renewable energy components is dependent on the heat source/sink to great extent, the conventional emulation in signal level only by manipulating the sensor and actuator signals will not be feasible any more. Thus, a multi-physics test platform including thermal, hydraulic and electrical interfaces as well as the data communication interfaces have been developed. The emulation of the operating environment of HES succeeds through the advanced weather and building simulation models and fast controllable facilities of the HiL test bed. The control logic of the HEMS is implemented as C-code in a Gateway of the HP system, which exists as a standalone embedment system for the regulation of whole HP system. In the following text, the essential parts of the dynamic validation approach will be briefly described. More detailed information about the design and development of the HiL platform can be found in (Chen, et al., 2012).

2.1 Numerical Simulation

Numerical simulation models have been developed in order to substitute physical components of the system under test. Therefore, the models have to be developed with real-time capability and later executed in real-time.

A floor layout of a single-family house model, composed of room models and a hydraulic network, has been developed in Dymola. The walls, windows, doors as well as the heat balance of thermal nodes, e.g. indoor air, furniture, for each room and the hydraulic system are physically modelled. Each wall in the building has two convective heat ports linking heat transfer between two sides. Each outside wall includes also a window model and an irradiative port that transmits the solar irradiance into the indoor air node. The heat loss due to the air exchange is considered in the dynamic differential equation of the room temperature (Böckh 2011). The insulation standard such as the number of insulation layers and the U-value of the inside and outside walls can be flexibly selected according to different norms. The hydraulic circuit of the model consists of radiator devices as well as inlet and outlet pipes. A thermal static valve is mounted in the inlet pipe of the radiator which regulates the heating power by changing the flow rate of the heating-circuit water in order to keep the room temperature at a desired level. The radiator measures the convective and irradiative temperature in the room and calculates the mean value as the current operative room temperature. The thermal coupling between radiator and indoor air is realized by connecting the convective and irradiative heat ports of both sides. This ratio is determined by the type and the geometry of the radiator. The heating power of the radiator is influenced by the inlet temperature and the flow rate of the heating water. The parameters of each room, such as dimensions, air exchange rate, insulation, and temperature set points can be configured individually.

2.2 Emulation Interfaces

The emulation system, which is developed for the dynamic validation of HP systems, comprises the hydraulic interface, the thermal interface and also the electrical interface. The interfaces emulate the simulated boundary conditions resulting from the numerical simulations at the terminals of the Hardware-under-Test. Figure 3 describes the emulation system and its interconnection to other system components such as the numerical models and the hardware/HEMS to be tested.

In order to emulate the thermo-hydraulic dynamics of HP systems and to connect HES components, a hydraulic interface is required. The Hardware-under-Test in this case could be exemplary a HP with a hot water storage system. The hydraulic circuits of the interface should be able to emulate the hydraulic states (fluid temperature, flow rate and pressure) rapidly to track the simulated conditions and acting as heat sources/sinks for different hardware. The precision of the control and measurement system is also an important factor which influences the validity of the HiL simulation results. Therefore, the hydraulic test bench should have fast and precise controllability and sufficient accuracy of measurement to satisfy the design requirements. The selection of the components, the construction of the hydraulic interface as well as the design and parameterization of controller will account directly for these requirements. The hydraulic interface connects different kind of components hydraulically and serves as dynamic heat sink or source. In this work, two heat sinks are used. One is for the space heating system in the building and the other is for the emulation of DHW load profile. Since an air-to-water HP is used here, the heat source is the outdoor air instead of the brine circulation system.

A climate chamber is designed as the thermal interface of the emulation system, in order to emulate realistic weather conditions for air-to-water HP. The physical states such as air temperature and humidity around the HP inside the chamber are controllable. The climate control system comprises 18 kW electrical heating capacity and 10 kW brined-based cooling system. Furthermore the humidity in the chamber is regulated by a steam humidifier. All the actuator systems are continuously and fast controllable so that the accurate dynamic outdoor climate for the HP can be emulated. The design of the temperature control system in the climate chamber is based on the two-degrees-of-freedom structure. The trajectories of ambient weather conditions such as temperature, humidity will be extracted from the "Test Reference Year" (TRY) which is authorized by "Deutscher Wetterdienst" (DWD 2012).

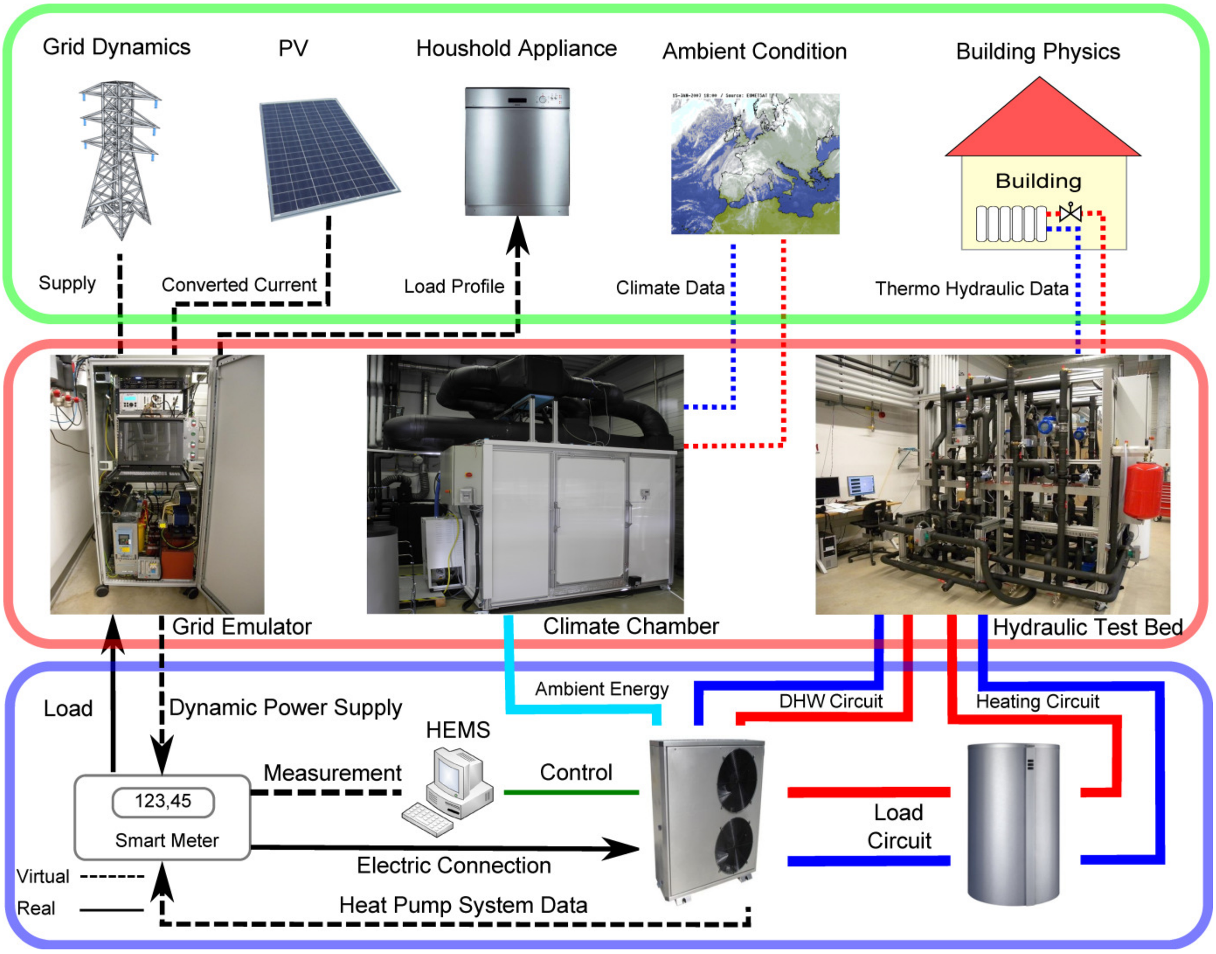

Figure 3 Interconnection of Emulation System to Other System Components

The HP is connected to a power converter which provides the electrical power connection and emulates the behavior of the electrical grid according to the simulation models. Moreover, the smart-grid capable HEMS is receiving not only the process signals from HP, but also the grid status from the smart-metering, in order to make the up-to-date decision if the demand response (DR) algorithm should be executed on the HP.

2.3 Interaction with HEMS Prototype

In order to validate the HP system based on HiL principle, two computing nodes are required: one node is the PC cluster and another is the HP gateway. The total simulation infrastructure and the data flow sequence between two nodes are depicted in Figure 4. In the PC cluster, the control program developed in LabVIEW communicates with simulation environment Dymola and the emulation hardware, so that the virtual and physical boundary conditions can be exchanged and converted. The prototype of the Controller-under-Test (HEMS), where the control logic of the HP system as well as the smart-grid functionalities such as DR algorithm are implemented, is compiled as a .dll-file and can be called by the LabVIEW control program in each communication cycle. The gateway cluster serves as a bridge between the

HEMS prototype in PC cluster and the Hardware-under-Test. On the zone hand, the control commands from the PC cluster and the sensor signals from the HP system by the gateway are transferred and exchanged through an Ethernet switch in TCP/IP protocol once per cycle. On the other hand, the gateway communicates with the HP system in real-time capable fieldbus protocol, such as CAN bus, with a higher frequency.

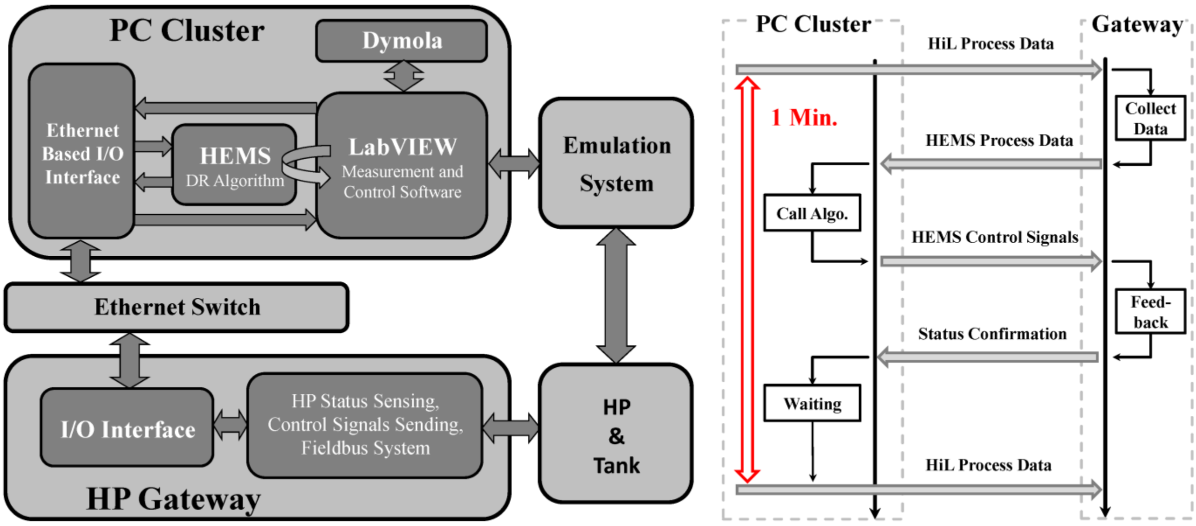

Figure 4 Data Flows in HiL Simulation Infrastructure

The data flow sequence between the two clusters in TCP/IP protocol is described in the right hand side of Figure 4. The sequence chart shows the content and direction of the data communication between two computing nodes in one cycle (1 minute). At the beginning of the cycle, the PC cluster sends the “HiL Process Data” to the gateway, including the measured signals in emulation system as well as simulated data from Dymola. These data will be logged in the gateway. The desired data will be processed and combined with HP measurement data into a new data cluster “HEMS Process Data”. After the LabVIEW control program receives this telegram, it will call the HEMS function with this data cluster as API (Application Programming Interface) data. The control decision of the HP system for this cycle will be made and sent to the gateway. When the gateway receives the data cluster “HEMS Control Signals”, the commands will be interpreted and sent to HP via fieldbus protocol. After successful execution of the control commands, a status telegram will be sent back to PC cluster in order to confirm the acknowledgement of the commands.

4 HEAT PUMP CONTROL SYSTEM DESIGN

Considering the HP system composition and its functional requirements, a modular design of HEMS is proposed, which contains four different functional modules. The compressor control module sends the modulation command to the HP so that the HP outlet temperature can be regulated; The tank unit control module decides when and how long the booster heater in the DHW tank should be activated; The three-way-valve module controls the current heating mode of the HP (tank or space heating); The HEMS is also equipped with a user interface module that receives the control parameters and settings specified by the user, such as heating curve, tank set temperature and so on.

The principle of the traditional heat pump control is depicted in Figure 5, which is based on the heating curve specified by user. A heating curve is given which defines for the HP the target outlet temperature (red) related to the current outdoor temperature. During the start-up phase of the HP, the compressor is fed with the rated frequency specified by the parameter table of the HP. When the HP outlet temperature accesses into the modulation band (±2 °C), the frequency will be modulated proportionally based on the rated frequency in order to keep the outlet temperature at the set point. Detailed explanation can be found in (Chen 2013).

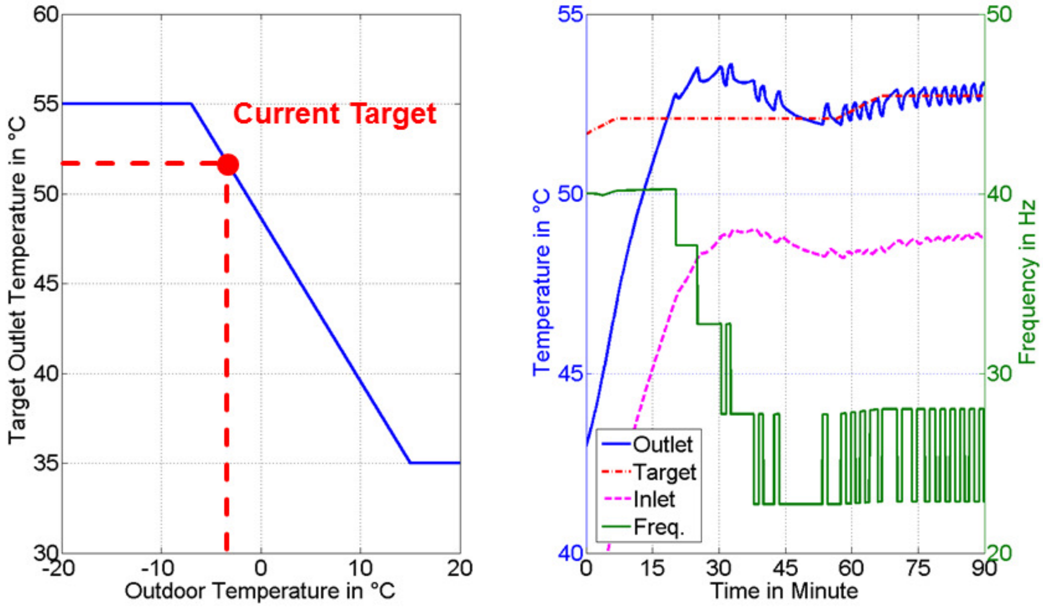

Figure 5 Heating-Curve Based Control

Although the heating-curve based control approach is widely used in heat pump systems, the limitation of it can be seen obviously: it is a weather-driven control principle and thus cannot react to the dynamic demand response. In order to develop a smart-grid capable heat pump system, the cascade control structure is proposed as follows (Figure 6).

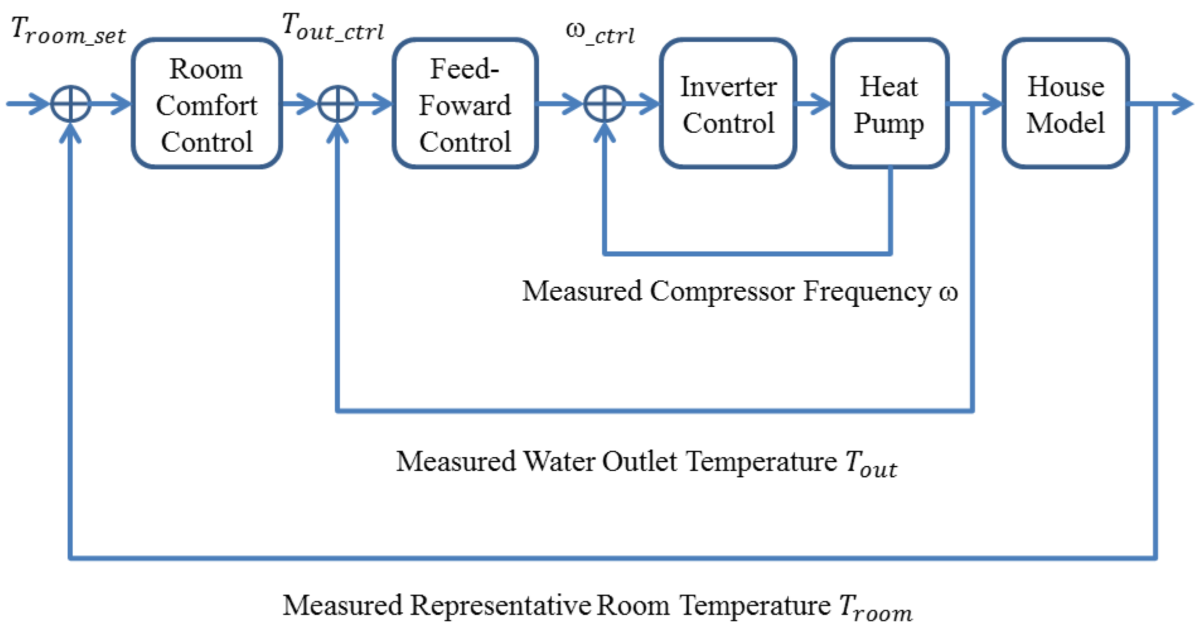

Figure 6 Cascade Heat Pump Control Structure

As shown in Figure 6, the cascade control structure comprises three sub-loops: the room temperature control, the HP outlet temperature feed-forward control and the compressor frequency control. The control module “Room Comfort” has the functionality to give the HP system an adaptive set point of outlet temperature based on current and required thermal conditions. Based on this information, the feed-forward control calculates the corresponding compressor frequency. And the internal loop coordinates the compressor, expansion valve and etc. in order to achieve the given frequency value. According to the functionalities, the room comfort controller can be integrated into HEMS as decision level; the feed-forward and frequency controls are implemented inside the heat pump as hardware level. The HEMS is linked to a smart gateway, which generates a dynamic room set temperature profile according to the load condition on the electrical grid for demand response.

The Smart-Grid capable HEMS should interact with the electrical grid through Smart-Metering in order to detect and relief the peak load profile on medium and low voltage grid. As a key point to Smart-Grid technologies, DR is used to encourage consumers to reduce demand, thereby reducing peak demand for electricity. Since electrical generation and transmission systems are generally sized to a certain peak demand, lowering peak demand reduces overall plant and capital cost requirements. The objective of DR is to actively engage customers in modifying their consumption in response to pricing signals, in order to reflect supply expectations through consumer price signals or controls, and to enable dynamic changes in consumption relative to price (Sianaki 2010). Hence, Demand response can be a more cost-effective alternative than adding generation capabilities to meet the peak or occasional demand spikes.

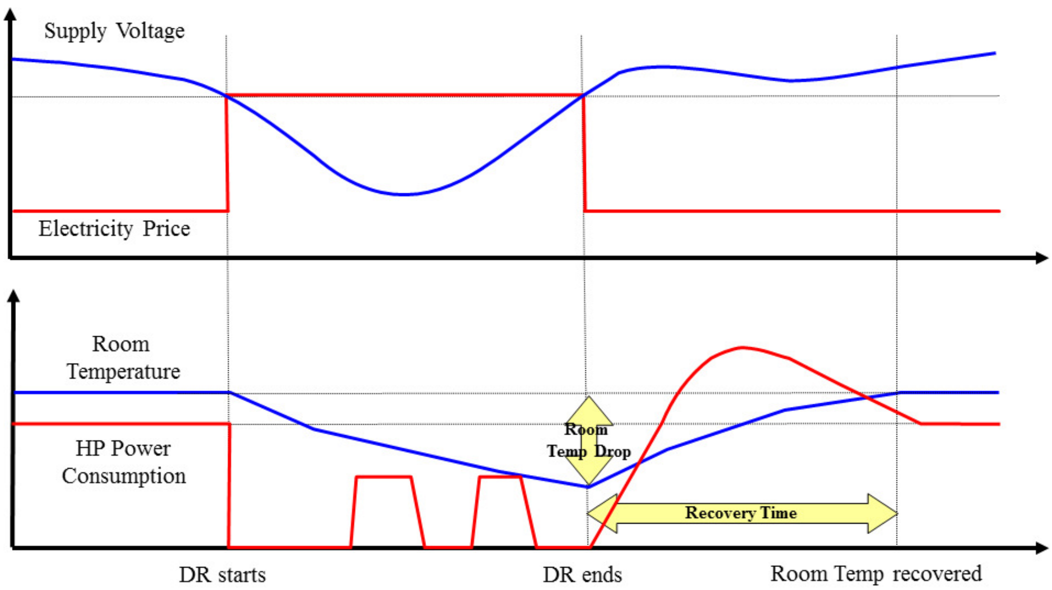

Figure 7 Principle of Demand Response

Figure 7 explains the functional principle of the DR algorithm used in this work. In the upper part, the profiles of supply voltage (blue) of HP and the electricity price tariff are shown. Since the voltage level is always used as an index to reflect the overall electrical load level in the grid, if the voltage drops out of the tolerance band, the start of the peak demand period can be detected. Normally, the peak demand period is identified by the power suppliers in a certain time slot during the day, which is directly dependent on the user presence in the local neighborhood. In order to encourage the users to reduce the power consumption during the time slot, a time-variant electricity tariff is adopted in this case, which increases the price compared to normal operation. The DR of the electrical HP systems plays a great role in the demand reduction on the electrical grid, since the space heating and DHW demands are the primary energy consumers in residential buildings. On the other hand, how to maintain the indoor thermal comfort during the DR is an important objective in the design of the HEMS. A speed-controlled HP system with the proposed cascade control structure (Figure 6) in this case provides the possibility to modulate the heating capacity during the DR. In the lower part of Figure 7, the HP power consumption (red) and the tendency of room temperature (blue) are implied. When the DR is active, the HEMS will receive a lower target outlet temperature profile from the smart gateway, which should fulfill the room temperature drop during DR specified by the user. After the end of DR, a higher modulation will be used in order to recover the room temperature back to comfort level inside a required time frame.

5 VALIDATION SCENARIO AND RESULTS

The functionalities and benefits of the proposed control structure and DR algorithm are to be validated based on the HiL approach (Figure 3), which gives the following advantages compared to traditional field trial during the prototyping phase: lower experimental cost, good reproducibility, high flexibility and safety. A typical one-family house with 10 rooms has been modeled in Modelica language. So that the HEMS can know and optimize the overall thermal comfort level in the building, a representative room temperature index T_{rep} is built, which can be formulated as follows:

$$T_{rep} = \boldsymbol{\varphi}^{\mathrm{T}} \cdot \boldsymbol{\theta}$$

Where the vector φ is the weighting factor of each room (Table 1); and θ represents the vector of sensed temperature of all those rooms. In the practical application, the weighting factors can be specified by user arbitrarily. In order to define a reasonable representative room temperature, which can reflect the overall thermal comfort level inside the building, the weighting factors of each room used in following validation test are specified based on the portion of the room space in the total living area of the building.

Table 1 Weighting Factors for the Calculation of Representative Room Temperature

Ground Floor	Weight	First Floor	Weight
Living Room North	13.34%	Bedroom 2	8.26%
Living Room South	23.14%	Bedroom 3	9.83%
Bedroom 1	10.3%	Bedroom 4	13.99%
Kitchen	9.7%	Laundry	5.75%
Bathroom 1	2.75%	Bathroom 2	2.94%

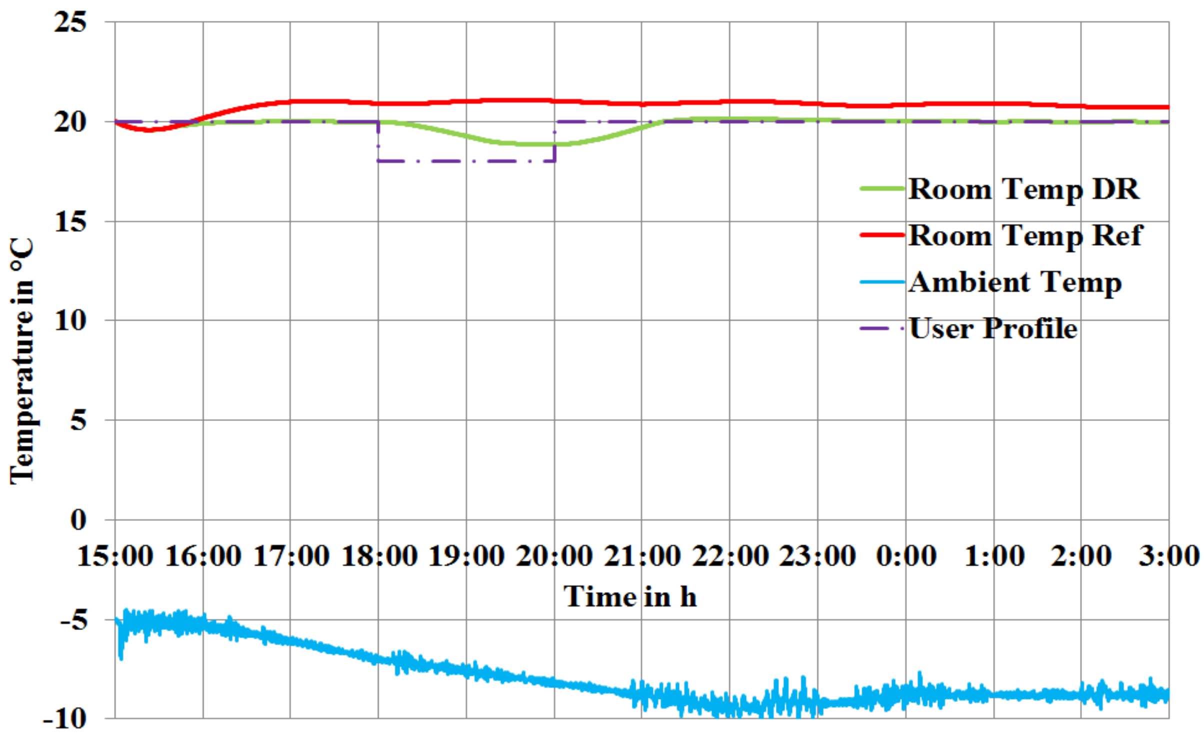

Figure 8 Representative Room Temperature Comparison

It is assumed that this single-family house is located in a standard climate zone DWD 5 in Germany. A typical ambient temperature profile in winter day is emulated by the climate chamber, which is described by the light blue curve in Figure 8. The observing HiL simulation time slot is from 15:00 PM to 3:00 AM, during which the DR normally occurs. In this test, a DR is assumed to start from 18:00 to 20:00 and the required room temperature during DR is reduced from 20 ℃ (in normal time) to 18 ℃ (see curve "User Profile"). In order to compare, a reference test has been conducted (red), where the traditional heating curve based outlet temperature control is implemented (Figure 5). The green curve depicts the representative room temperature according to the proposed control strategy in Figure 6. Based on the facts from comparison, the traditional control concept of air-to-water HP system cannot regulate the room temperature very exactly at the desired level, which may raise the unnecessary energy consumption. It is also not capable to react to DR function, which is driven by a smart gateway. On the other hand, the proposed DR algorithm can keep the house accurately at the required temperature. The representative room temperature during peak period is above required temperature (18 ℃). And the representative room temperature after recovery phase is also controlled at about 20 ℃ ($< \pm 0.1$ ℃).

In order to avoid overshoots and fluctuations causing energy inefficiency in HP control system especially during transient phase, an intelligent switch logic in room temperature control module is implemented, which helps the controller to recognize and avoid saturation risks and therefore to eliminate big overshoots. As the result shows, the recovery phase takes less than 1 hour and there is no obvious overshoot or fluctuation provoked, causing no significant discomfort to user.

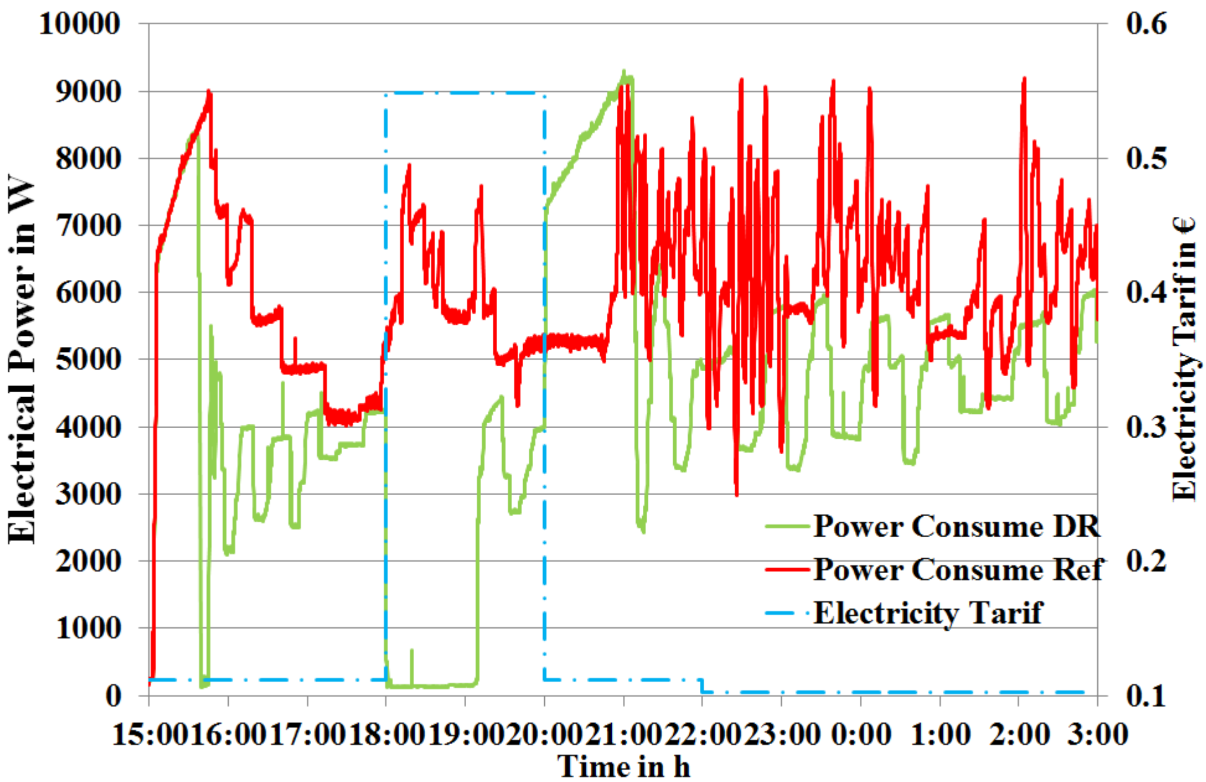

Figure 9 Power Consumption Comparison

The comparison of the power consumption is visualized in Figure 9. As shown, the DR algorithm (green) has a smoother modulation than the reference one (red), which means better energy efficiency and better components' life time conservation. Total electrical energy consumption during peak period is reduced by about 64% through the DR algorithm, but recovery peak power created by algorithm after peak period is about 64% more than usual. Overall total electrical energy consumption during & after peak period is reduced about 28%

by the algorithm. The electricity tariff plays an important role that drives the DR through user. In order to investigate the benefit brought by DR algorithm, tariff information provided by (EDF 2013) is represented in light blue curve in Figure 9. The price will increase from 0.112 €/kWh in the normal period to 0.5488 €/kWh during the peak load period. Based on this tariff, it can be calculated that the overall electricity costs during & after peak period is reduced about 4.17 € by DR algorithm compared to the reference case.

6 CONCLUSION

In transition to renewable home energy systems, more and more HP systems will be integrated in the electrical grid. The Smart-Grid technology is getting more relevance to equalize the load profiles and reduce the peak load of the grid. As one of the most important Smart-Grid solutions, DR algorithm is introduced which is based on price-driven mechanism. The design focus of the modern HEMS for HP system is to provide the DR algorithm which optimizes electricity cost, reduces peak load, but also guarantees the indoor comfort meanwhile. In order to validate the integration and the functionalities of the HEMS, the HiL simulation approach has been presented. The proposed HiL simulation platform, including simulation models, emulation test bed and the hardware to be tested, allows for running combined signal and power level HiL simulations for residential HP systems. This approach is used to support the design process of smart HP systems by applying the concept of incremental prototyping. Based on a typical installation of residential air-to-water HP system, the working principle of DR algorithm is described and the benefit against traditional HEMS for HP system is validated and quantified through a HiL test.

7 REFERENCES

Farhangi H. 2010. “The Path of the Smart Grid” In: IEEE Power and Energy Magazine.

Monti A., F. Ponci. 2010. “Power Grids of the Future: Why Smart Means Complex.” In: 2010 Complexity in Engineering, Roma, Italy.

Huchtemann K., D. Müller 2011. “Evaluation of Field Study Data on Domestic Heat Pump Systems” In: E.ON Energy Research Center Series. – Volume 3, Issue 2.

Grosch, V., H. Schmidt. 2008. “Hardware-in-the-Loop Technology: Quo Vadis?” Sindelfingen, Daimler AG.

Majstorovic, D., I. Celanovic, N.D. Teslic, Katic. Oct. 2011. “Ultralow-Latency Hardware-in-the-Loop Platform for Rapid Validation of Power Electronics Designs” In: IEEE Transactions on Industrial Electronics, vol. 58, no. 10, pp. 4708-4716.

Steurer M., C.S. Edrington, M. Sloderbeck, Ren. Apr.2010. “A Megawatt-Scale Power Hardware-in-the-Loop Simulation Setup for Motor Drives.” In: IEEE Transactions on Industrial Electronics, vol. 57, no. 4, pp. 1254-1260.

Maclay. 1997. “Simulation gets into the loop.” In: IEEE Review, vol. 43, no. 3, pp. 109–112.

Li H., M. Steurer, K. L. Shi, S. Woodruff. Jun.2006. “Development of a Unified Design, Test, and Research Platform for Wind Energy Systems Based on Hardware-in-the-Loop Real-Time Simulation” In: IEEE Transactions on Industrial Electronics, vol. 53, no. 4, pp. 1144-1151.

Li W., G. Joos, J. Belanger. Apr. 2010. “Real-Time Simulation of a Wind Turbine Generator Coupled with a Battery Supercapacitor Energy Storage System.” In: IEEE Transactions on Industrial Electronics, vol. 57, no. 4, pp. 1137-1145.

Chen, K., R. Streblow, D. Müller, et al. 2012. “Hardware-in-the-Loop Test Bed for Home Energy Systems.” In: E.ON Energy Research Center Series. ISSN: 1868-7415.

Böckh, W. 2011. Heat Transfer: Basic and Practice, Springer-Verlag, Berlin Heidelberg.

DWD. 2012. Deutscher Wetterdienst is a public institution under the Federal Ministry of Transport, Building and Urban Development which is responsible for meeting meteorological requirements in all areas. http://www.dwd.de/ [Online].

Sianaki, O.A., O. Hussain, T. Dillon, A.R. Tabesh. Sept. 2010. “Intelligent Decision Support System for Including Consumers’ Preferences in Residential Energy Consumption in Smart Grid” In: Computational Intelligence, Modelling and Simulation (CIMSiM), 2010 Second International Conference.

Chen, K., R. Streblow, D. Müller, 2013. “Simulation Based Design and Validation of Home Energy System.“ In: 2013 Building Simulation Conference, Chambery, France.

EDF, 2013. http://particuliers.edf.com/gestion-de-mon-contrat/options-tempo-et-ejp/option-ejp/details-de-l-option-52420.html.