12th IEA Heat Pump Conference 2017

Virtual test bench by linking the "FHNW - Energy Research Lab" and the "HSLU - NODES Lab"

Christoph Messmer[a], Christof Ackermann[a], Robert Spoerri[b], Christoph Dahinden[b], Thomas Afjei[a,]*, Matthias Sulzer[b]

[a]University of Applied Sciences and Arts Northwestern Switzerland, Institute of Energy in Building, St. Jakob-Strasse 84, 4132 Muttenz, Switzerland
[b]*Lucerne University of Applied Sciences and Arts, Center for Integral Building Technologies ZIG, Technikumsstrasse 21, 6048 Horw, Switzerland*

Abstract

Test benches are designed in regard to their specific purpose. The system boundaries, the hardware and control algorithms vary from one lab to another. Whereas one lab may emphasize e.g. on thermal low temperature networks another lab may focus on components for building control. Specific tasks and research questions demand the combination of both test benches. This «Virtual Test Bench» takes advantage of the individual benefits of each laboratory such as hardware, e.g. heat/cold source, emulated building dynamics or special control features. To be fully operational a connection between the two test benches is needed, referred to as «Livelink», where data can be exchanged interactively and transferred at high speed. The «LiveLink» connects the two platforms to answer system overlapping questions. In this work the «Livelink» between two test benches located at two Universities of Applied Sciences 80 km apart, is described, its operation modes explained and first results are presented.
The Energy Research Lab (ERL) of the FHNW is used to examine the dynamic behaviour and the appropriate integration of hydraulic systems for space heating and domestic hot water. To avoid depending on a mere computer simulation, component behaviour in ERL can be reproduced by both «emulators» and real components. Heat pumps and hot water storage tanks for instance can be connected to the emulation modules acting as source and sink (Hardware in the Loop). Summarized, the ERL allows to run dynamic tests under predefined and repeatable boundary conditions.
The NODES Lab of the HSLU addresses the decentralized thermal energy supply infrastructure. Its focus lies on the development of thermal crosslinking aiming to realize Multi-Energy-Grid infrastructures for «Urban Energy Systems».

Keywords: Hydraulic Systems in Buildings; Low Temperature Network; Multy Energy Grid; Urban Energy Systems; Energy Research Lab; Nodes; Livelink; Simulation; Emulation; Hardware in the Loop; Virtual Test Bench; System control

1. Scope

1.1. Project goal

The project goal is to enhance the testing capabilities of two independent test benches 80 km apart by coupling them with a fast and secure data communication. This yields to a virtual test bench with the main objective to enable a holistic testing environment, consisting of a low temperature network (LTN) implemented within the NODES Lab and a dynamic building load emulated with a multi-zone house model at the ERL using the LiveLink.

* Dr. Thomas Afjei. Tel.: +41-61-467-4349; fax: +41-61-467-4543
E-mail address: thomas.afjei@fhnw.ch

1.2. Importance of the results for practical use

Coupling test benches in order to enhance the versatility of systems to be measured and an improved matching of system characteristics with reality are very beneficial. Simplified e.g. just steady-state boundary conditions for measurements are often the reason, why problems of real systems cannot be reproduced with standard testing conditions.

In this research, the possibility to integrate HIL (Hardware-in-the-loop) components is a key factor to provide a realistic behavior of a measured heat pump heating system linked to a LTN.

Connecting the two systems, in this case the heat pump with the low temperature network NODES, allows an accurate representation of decentralized energy systems and is therefore a valuable tool to analyze and evaluate its system dynamics and interacting.

1.3. Energy Research Lab (FHNW)

To avoid depending on a mere computer simulation, the Institute of Energy in Building at FHNW realized the Energy Research Lab (ERL) shown in Fig. 1 with focus on optimizing plant components and system integration of heat pumps for space heating and domestic hot water.

Main feature of the ERL is the dynamic testing capability of components and combined systems.

Fig. 1 Energy Research Lab at the FHNW

The ERL's dynamic tests can be run under predefined and reproducible conditions. Real components, so called Hardware-in-the-loop, e.g. heat pumps and hot water storage tanks are connected to emulation modules acting as heat source and sink. A real-time simulation provides the set points to control temperature and volume flow.

Fig. 2 depicts the ERL components. The central component is a heat pump that supplies heat for space heating, as well as for domestic hot water (DHW) generation. Depending on the type of the heat pump (brine-water / air-water) different sources can be chosen. 13 standard circuits are predefined and also project specific combinations can be set up. All components can be run as emulation based on a simulation model. Apart from the borehole heat exchanger and the space heating, all the shown devices are available as real components and can be integrated into a test setting.

Due to these properties an assessment of the dynamic characteristic of various technical systems as well as the whole building system is possible.

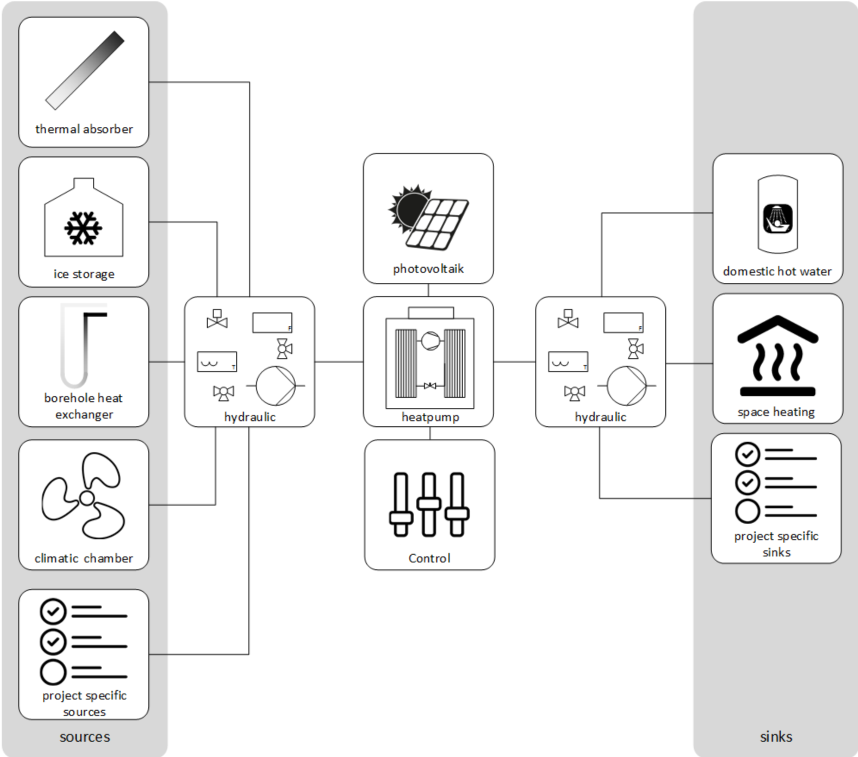

Fig. 2 Schematic representation of the Energy Research Lab

1.4. NODES Lab (HSLU)

With the test bench "New Opportunities for Decentralized Energy Systems" (NODES, Fig. 3) the thermal cross-linking of a simplified district with three consumers, a seasonal storage and a heat source in laboratory size is set up. Its focus lies on the infrastructure of the network, whereas the heating and cooling profiles of both consumers and suppliers can be emulated, following a real-time simulation.

The NODES Lab focuses on the future development of thermal crosslinking, from linear, unidirectional to bidirectional ring topologies and multiple meshes, aiming at a holistic Multi-Energy-Grid infrastructure for "Urban Energy Systems".

The applied research of the thermal crosslinking is addressed to low temperature networks (LTN) with system temperatures of <25 °C, where the energy is upgraded via heat pumps. Such networks can be operated as bi-directional networks and include both heat sources and heat sinks. Ideally, the two energy flows compensate each other at all times. Existing excesses or deficits need to be compensated by heat supply to or heat extraction from the network or storages (i.e. geothermal storage, PV plant, etc.).

Fig. 3 Nodes Lab at the HSLU

The detailed hydraulic scheme of the NODES lab including the ring network, with its cold and warm duct, and its consumers / suppliers including the heat exchangers, pumps, valves, measuring devices and internal storages are shown in Fig. 4. The bold frame on the left side of Fig. 4 highlights the LiveLink junction node.

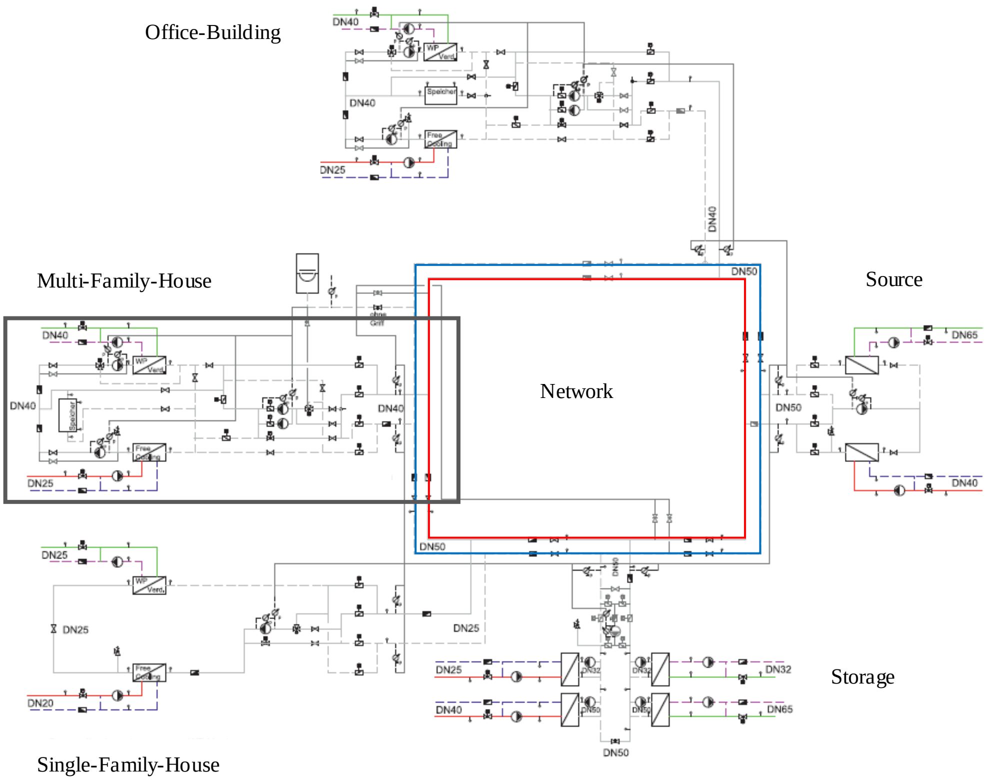

Fig. 4 Overall NODES Lab Schematic with bold frame marked LiveLink junction node

The second schematic (Fig. 5) shows the LiveLink junction node in detail. The green area represents the in-/outflow branches of the network. The red area is active when heating is being supplied to the network in case of Free-cooling. Across the second heat exchanger for heating energy is being extracted from the network (in green) to the virtual network participant (in blue). It represents the system boundary between the NODES network and the actual building / heat pump at the ERL Lab. During LiveLink activation the ERL Lab calculates the load set point which needs to be extracted from the NODES network based on direct measurements of the heat pump in operation. The corresponding control valves of the NODES Lab then regulate the transmitted load across the heat exchanger.

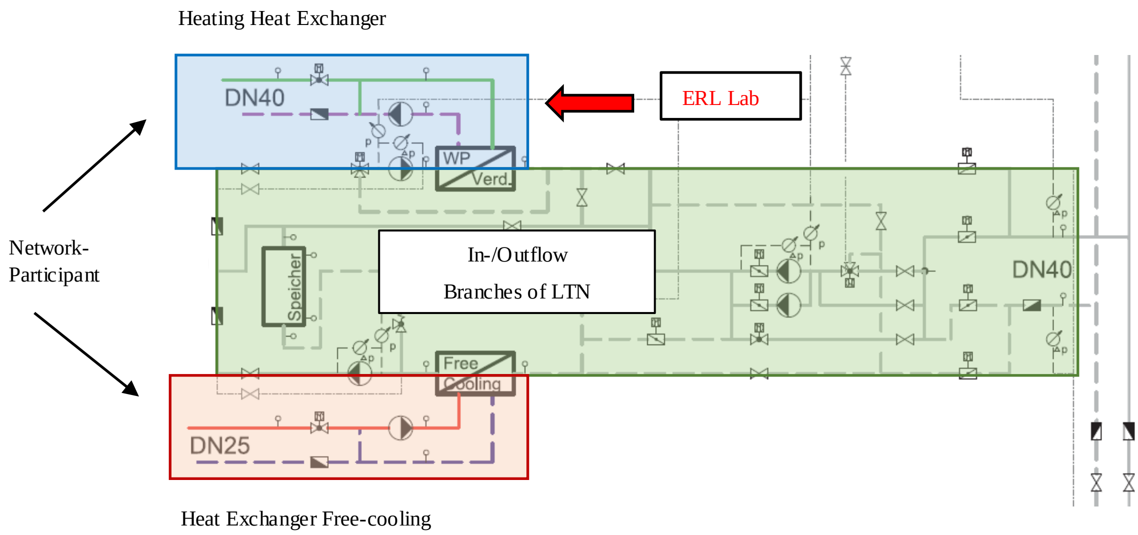

Fig. 5 Detailed schematic of the Multi-Family-House consumer of the NODES Lab
highlighting the system boundary between the network and the junction node to the ERL Lab.

2. **Methods**

The required methods to perform tests with connected labs are on two physical levels.

One concerns the basic data exchange capabilities, i.e. the required IT to make the data readable for the partner lab. Security issues are most critical. Routed firewall channels on both sides ensure a safe operation and restrict unauthorized access.

The second one covers the real scale machinery, its hydraulics, the thermal behavior, as well as the control and measurement system.

2.1. Required data communication

For an interaction of the two laboratories a fast and secure data communication is needed. The Siemens S7® controller of the NODES Lab provides the necessary Siemens proprietary S7 communication protocol. It is designed for PLC programing (Programmable Logic Controllers), diagnostic purposes, exchanging data between PLCs and accessing data from SCADA systems (Supervisory Control And Data Acquisition).

To use this protocol, a direct IP connection between the FHNW Labview® PC and the HSLU S7 PLC was realized, requiring a correct configuration of both firewalls (Fig. 6).

During communication initialization, the ERL LiveLink software (**1**) establishes the connection to the HSLU S7 PLC (**2**). The LiveLink software is then able to read and write data from and to the PLC and builds the bridge between the simulation based system control (XPC Target (**3**), FHNW ERL) and the LTN control (S7 PLC, HSLU NODES Lab (**2**)).

The activation of the LiveLink mode within the NODES Lab LTN control is set by a manual switch restricting the access from the ERL Lab.

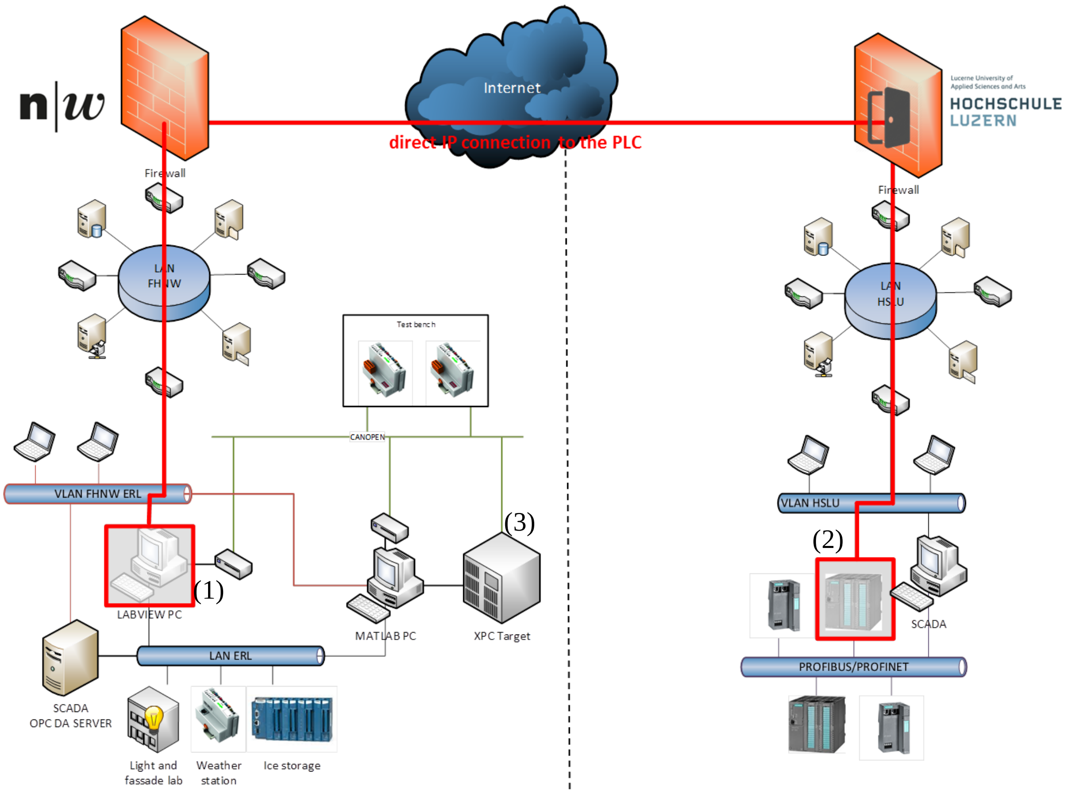

Fig. 6 IT-Concept and structure ERL and NODES Lab

2.2. Tested hardware and exchanged parameters

The heat pump, which is being tested at the ERL with emulated loads, feeds its heating profile to one of the consumers of the Low Temperature Network (LTN) within the NODES Lab. The heating and cooling profiles of the remaining prosumers are virtual and uploaded to the NODES network via a separate Labview® software.

In the following section the individual steps during a single loop of the data communication sequence is explained (Fig. 7):

(1) Initial situation: The current state and the actual values of the LTN are backed-up by the measurement and control system (PLC) of the NODES Lab.

(2) Extraction of thermal network data:
The LiveLink software reads the relevant data, the inlet volume flow and the inlet temperature of the NODES heat exchanger and sends them to the Matlab/Simulink® simulation model of the ERL.

(3) Control of heat pump source emulator:
The simulation takes these output values as set (input) values and regulates the outlet volume flow and the outlet temperature of the heat pump source emulator.

(4) Operation of the heat pump: The heat pump is operated according to the present building heat load determined by the temperature set-point of the load emulator of the ERL.

(5) Resulting extracted thermal power (calculated):
The Simulink model then calculates the thermal power with the measured inlet volume flow and the inlet- and return temperature of the heat pump.

(6) Feedback of heat pump response to NODES Lab:
Next, the Live-Link software reads this effective thermal source power and sends the data back to the NODES lab.

(7) Actuator control within NODES Lab:
The PLC takes the obtained response set value, the thermal power, to regulate the power extracted from the NODES network across the heat exchanger of the defined building component.

(8) Real time simulation: The sequence repeats with a frequency of 1Hz.

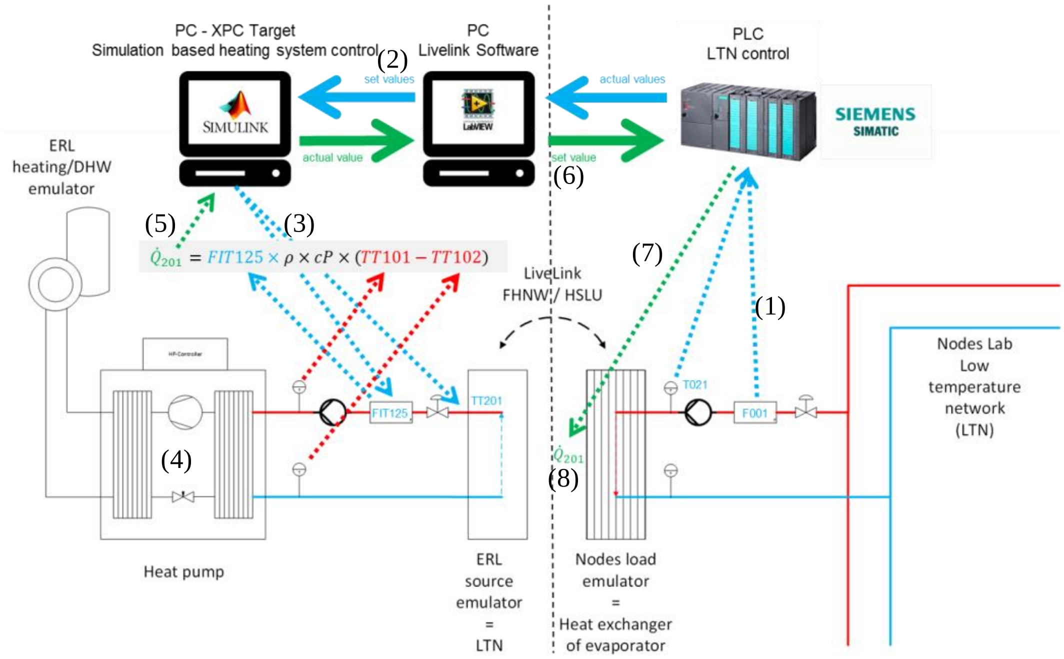

Fig. 7 Parameter exchange overview ERL and NODES Lab

2.3. Adapting the control systems of the NODES Lab and ERL for LiveLink

After establishing communication, the two control systems had to be set up for correct combined testing.

The NODES Lab uses timed thermal load profiles according to either real measurements or artificial data to operate the LTN in the various configurations and operating points.

The load input software of the NODES Lab was enhanced to receive external real-time load values from the ERL. These ERL load values are calculated from measurements of the heat pump in operation.

In standard operation the ERL is using a simulation to feed the heat pump controller with the house and environmental data. The source and load emulators are controlled by the simulation based on physical models.

The ERL heat pump was configured as a slave device. The master control comes from the simulation in form of a demand signal.

2.4. Heat pump operation sequence

For the initial LiveLink tests, a schedule for the heating demand (on/off) and the load has been used as depicted in Fig. 8. Later tests will be carried out with fully simulated data.

For all performed tests the heat pump was turned on twice for time periods between 30-45 min with a break of 15 min in between. In addition, the load temperature was changed from 28°C to 50°C, then back to 28°C during the first running period in order to alter the source power.

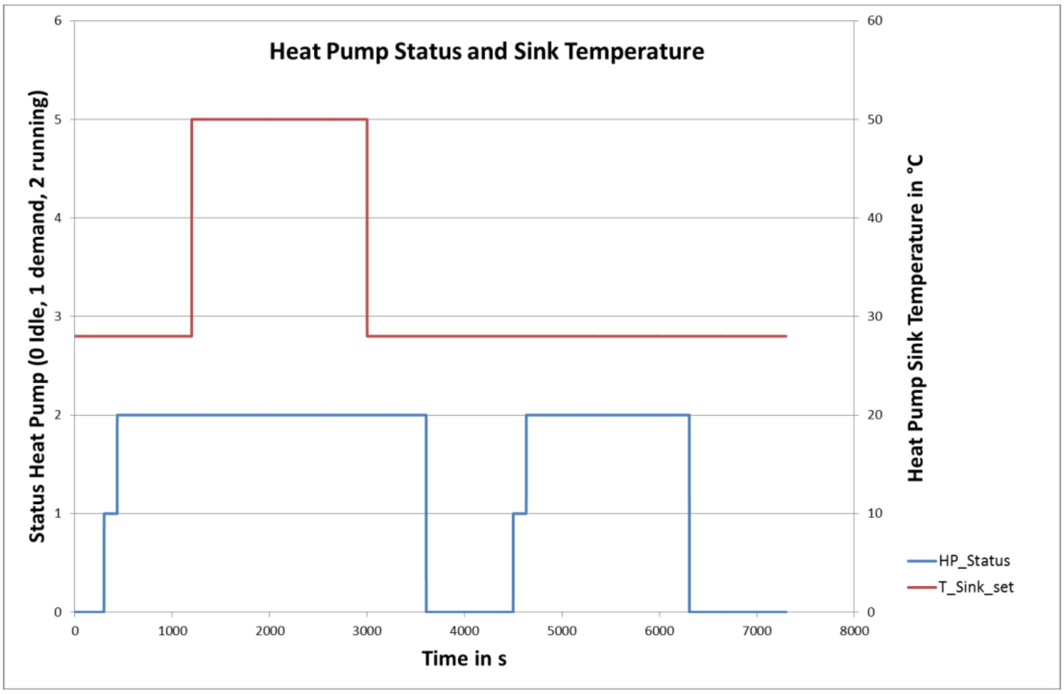

Fig. 8 Heat pump operation schedule with master signal on/off and load temperature

The ERL sends a heat pump status to the NODES Lab to inform about its condition. It has the following values corresponding to:

0: IDLE (Heat pump is powered on but on standby)
1: DEMAND (Heat pump starts its run-up procedure, signal for NODES Lab to start consumer)
2: RUN (Heat pump controller releases compressor start)

The start-up of the 8.4 kW (B0/W35) heat pump has a manufacturer defined schedule according to Fig. 9. When receiving the heating demand signal from the simulation the heat pump controller starts the source pump. This is used to sense the source for sufficient temperature for the compressor start release. After about 2 minutes the heat pump controller starts the compressor. Approximately 1 minute later, the source volume flow is regulated by the simulation model in order to maintain a specified temperature difference across the heat pump vaporizer (here 4K).

The hydraulics and control system of the NODES LTN are capable to represent both: decentralized and centralized energy systems. In addition, topologies can be realized linear or using a ring / mesh setup.

In a decentralized LTN ring topology, the NODES Lab starts the circulating pump of its “multi-family-house” consumer source pump simultaneously with the activation of the ERL source pump.

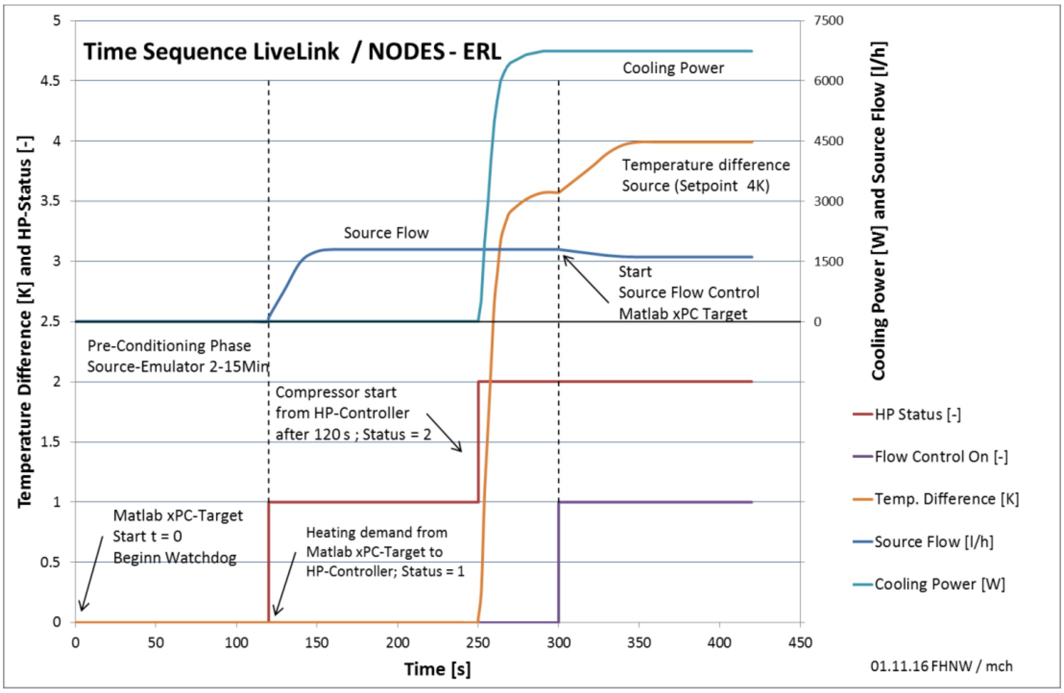

Fig. 9 Heat pump start sequence

2.5. Performed LiveLink tests

Several tests were performed with two basic NODES LTN setups according to Table 1.

The first three tests were performed in order to ensure a reliable data connection and required fine tuning of both control systems allowing for proper operation of the two labs.

Table 1 Performed LiveLink Tests

Test	NODES LTN Topology/Setup	Consumer setup	Source	LTN initial ring temperature
No. 1-5	Decentral feeding pumps Ring topology	Domestic heating, no internal building storage	Borehole-heat exchanger without active pump	12°C
No. 6	Central feeding pump over source, uni-directional	Domestic heating, no internal building storage	Heat source, without borehole-heat exchanger	14°C

3. Results

The results of "Heating and Cooling Power" and "Heat Pump Temperatures" are depicted in Fig. 10. They are based on the 2 hour LiveLink test performed according to Table 1.

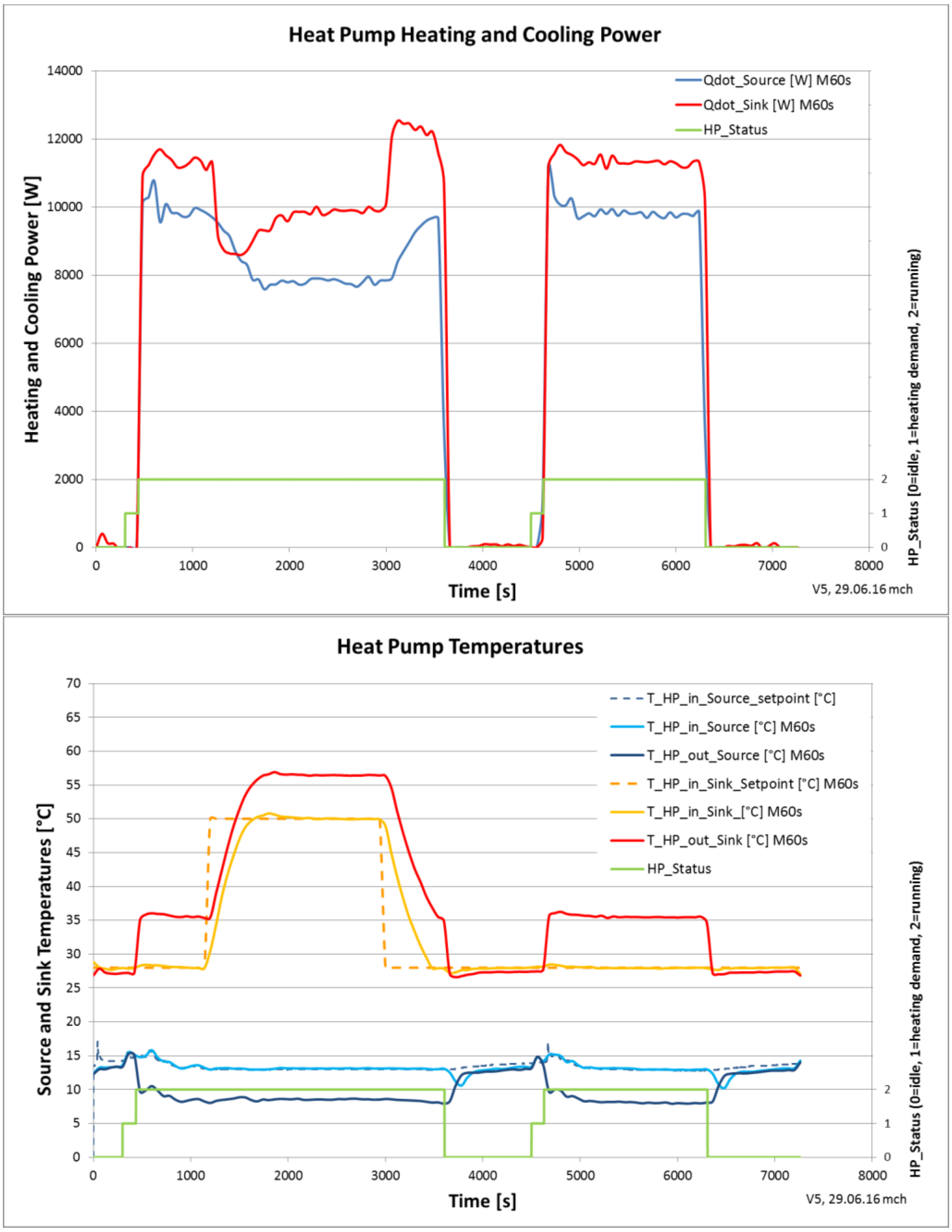

Fig. 10 Test No. 5 ERL heat pump power and temperature plots

Test No. 5 exemplarily shows the smooth interaction within the combined NODES Lab – ERL system. The reactions of the NODES LTN on the heat pump operation and the influence of the extracted power from the ERL are accurate. The results of the first three tests (No.1-3) indicated the need to tune the controllers and adapt the LiveLink communication parameters. Also, the ERL Matlab/Simulink® program was modified to send the heat pump status signal to the NODES Lab PLC system.

System control induced effects like oscillations were detected and investigated. Sudden power changes during heat pump start-up are system disturbances. Therefore, the heating control valve function of the consumer No.2 was enhanced with a feed-forward control improving its response time.

Test No. 6 was performed with a different network setup using a different source. Here, preliminary tests were performed to observe the control behavior. After the correct PID controller adjustment additional testing will be done.

4. Discussion

The initial tests and control adaptations of the two labs were necessary to ensure a smooth and realistic interaction of the combined lab.

System control induced effects like oscillations were observed and carefully investigated.

The time delay of the data exchange is small but not negligible for sudden power changes during the heat pump start-up phase. The data acquisition loop is timed with 1 second. During this period, all exchanged values are kept constant until the next loop.

The data transmission is about 10 times faster and therefore not limiting the loop time. From 968'000 sent data requests from the ERL, the response time was under 0.1 seconds in over 90% of the cases. The overall value range was between 0.05 - 0.55 seconds.

As the NODES lab does not include a heat pump itself, time steps of 5-15 min are suitable for uploaded heating and cooling profiles in standard operation. The slow reacting valves installed within the NODES lab are suitable to emulate such input data. During LiveLink activation a more dynamic situation results as the real behavior of the heat pump comes into play.

The control valve functions of NODES consumers were thus enhanced with a feed-forward control in order to cope with the fluctuations and react accordingly.

The effects resulting from the limitations of the two independent test facilities have to be identified and analyzed further.

Overall, it is most important to verify during each test, whether the installed components are influencing the system and thus performing as predicted.

Only then can the system performance be measured with realistic accuracy.

5. Perspectives

Initial tests were performed with a high thermal inertia LTN setup, were the thermal loads are small compared to the thermal mass of the LTN. During the heat pump operation, the LTN temperatures were remaining constant. Further tests will be performed with adapted inertias to observe the ring temperature floating.

The storage module (Fig. 4) represents a borehole heat exchanger system, scalable from a single exchanger to a field of exchangers. The thermal behavior is based on a corresponding simulation currently using a heat capacity model. Future refinements of the model are planned to take the detailed soil layers and the borehole field geometry into account.

The combination of simulation models, monitoring data of existing pilot projects and the complementary lab network “NEST-NODES-ERL” will serve as rapid prototyping tool and allows a holistic cover of a scaled urban Multi Energy Grid/Energy Hub (MEG/EH) infrastructure.

Including the knowledge of industry concerning market requirements with the achievements of research, standardized and pretested technologies for ready to market MEG/EH systems can be provided for planers, engineering and manufacturing companies.

Research on “Pressure Fluctuations in LTN and their Influence on the Operation of Heat Pumps” will be taken as reference test case.

Acknowledgements

We would like to thank the involved companies and parties, the CTI and all participants of the FHNW and the HSLU for their contributions and giving us the opportunity to realize this project.

References

[1] Sulzer M., Menti U.-P., Multi-Energy-Grid - Möglichkeiten der thermische Vernetzung, Zentrum für Integrale Gebäudetechnik, Hochschule Luzern – Technik & Architektur, AQUA & GAS No. 7/8 2015

[2] Sulzer M., Menti U.-P., Spoerri R., Maschen und Knoten, Zentrum für Integrale Gebäudetechnik, Hochschule Luzern – Technik & Architektur, TEC21 34/2015

[3] Wittwer C., Wille-Haussmann B., SmartEnergyLab, Fraunhofer-Institut für Solare Energiesysteme ISE, March 2014

[4] Ferrari M. L., Traverso A., Pascenti M., Massardo A. F., Plant management tools tested with a small-scale distributed generation laboratory, Thermochemical Power Group (TPG), DIME, University of Genoa, Italy, Journal, Energy Conversion and Management 78 (2014) 105–113

[5] Velvelidis V., Hollinger R. and Wittwer C., Hardware-in-the-Loop Testing of Control Strategies for Distributed Generation in the Smart Grid, Department Smart Grids, Fraunhofer Institute for Solar Energy Systems ISE, Energy Technology 2014, 2, 100 – 106

[6] Molyneaux A., G. Leyland G., Favrat D.*), Environomic multi-objective optimisation of a district heating network considering centralized and decentralized heat pumps, *) Industrial Energy Systems Laboratory, Ecole Polytechnique Federale de Lausanne (EPFL), CH1015 Lausanne, Switzerland, Energy 35 (2010) 751–758

[7] Lund H. a), Werner S., Wiltshire R., Svendsen S., Thorsen J. E., Hvelplund F., Vad Mathiesen B., 4th Generation District Heating (4GDH) Integrating smart thermal grids into future sustainable energy systems, a) Department of Development and Planning, Aalborg University, DK-9000 Aalborg, Denmark , Energy 68 (2014) 1-11