CoSES Laboratory for Combined Energy Systems At TU Munich

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Abstract—**This paper describes a newly built laboratory at the Research Center for Combined Smart Energy Systems (CoSES) at TU Munich. The laboratory is designed to provide a facility for analysis and testing of integrated energy systems (electricity, heating, cooling, e-mobility) in a holistic manner, which is recognized as a necessary approach in successful transition to sustainable energy systems. A distinct characteristic of the CoSES laboratory, besides the multi energy approach, is the full emulation of high power energy grids without the usage of real-time simulators. The control subsystem is based on the NI real-time hardware, while the NI VeriStand platform provides easy transition from the software models to the hardware prototypes.**

Keywords—Power-Hardware-in-the-Loop, microgrid, smart energy systems, integrated energy systems, emulation.

I. INTRODUCTION

A transition to more climate friendly energy systems imposed significant changes in their planning and operation [1]. These changes are characterized by intensive exploitation of renewable energy sources, such as solar and wind, and more efficient operation of the system through the use of Information and Communication Technology (ICT) systems. Exploiting the property of electricity to be easily converted to different types of energy and the trend of extensive electrification of heating, cooling and transportation energy systems through wider adoption of micro CHP systems, heat pumps and electric vehicles, power system is widely recognized to play a role of a backbone of the future integrated energy systems.

These changes have brought a paradigm shift in the power system operation but also imposed several challenges that are the focus of power systems research community, such as analysis of dynamic behavior in low inertia systems, undispatchable and uncertain energy sources, unpredictable power flows, etc. The distribution systems, which are traditionally designed as passive radial grids, have to be restructured to incorporate a new concept of prosumers and bidirectional flows. This has led to the introduction of the microgrid concept, which assume controllable entities that are able to reliably supply power to consumers even without connection to the wide area synchronous grid.

Even though the microgrid concept has been extensively investigated in the literature [2],[3],[4], the research topics are mainly focused on pure electrical system. There are also laboratories and demonstration sites around the world [3],[5],[6], however, to the authors best knowledge, there are no laboratories in the world specifically focused on investigating the different energy systems with their interdependencies in a holistic manner.

To address this gap, the Research Center for Combined Smart Energy Systems (CoSES) at Technical University Munich (TUM) has been established with a laboratory facility that is capable of emulating a small microgrid that consists of heating, cooling, transportation and electric subsystem. With the aim to provide a test environment with conditions close to those in real-life, the laboratory is equipped with the full set of high power components that practically eliminates a need for modeling in tools such as real-time simulators.

This paper presents a detailed architecture of the newly built laboratory. The laboratory emulates a small microgrid that consists of 5 buildings/houses of different sizes with fully controllable electric and heat demand including distributed electric and heat energy generation. These buildings are connected with a flexible electric and heat grid. The main components of the experimental system are:

- Flexible electric grid that consists of an experimental and a feedback grid;
- Distributed generation, Battery energy storages, EV charging stations;
- Fully controllable domestic electric consumption/ production;
- Bidirectional district heating/cooling grid;
- Domestic consumption with distributed heat sources (heat pumps, CHPs, Solar thermal);
- Control and monitoring infrastructure

In the remainder of the paper, each of these components will be described in detail. Section II gives an overview of the laboratory architecture. Section III and Section IV describe electric and heat subsystems, respectively, while the control and monitoring infrastructure is described in Section V. Section VI provides research potential, while design considerations are briefly discussed in Section VII. The conclusions are drawn in Section VIII.

The authors acknowledge support of the Bavarian Government and Deutsche Forschungsgemeinschaft (DFG) under project number 350746631.
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II. OVERVIEW OF THE LABORATORY ARCHITERCUTE

The laboratory emulates a small microgrid that consists of 4 single-family houses and 1 multi-family house with integrated heat, electric and communication layer (Fig. 1). Each house represents a prosumer in terms of both electricity and heat. The buildings are connected with a distribution electric and heat grids. In addition, the electric and heat grids are coupled through the CHPs and heat pumps, which essentially integrate these two energy systems into one entity. Two electric vehicle charging stations include transportation system into the test microgrid as well.

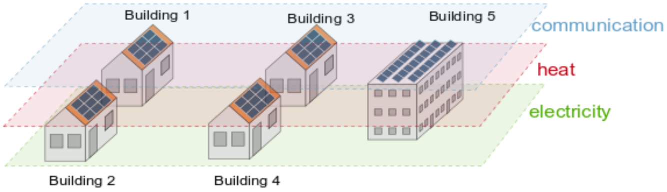


Fig. 1 Laboratory Oveverview

In the following paragraphs, different subsystems will be described.

III. ELECTRIC SYSTEM

A. Electric distribution grid

A single line diagram of the default configuration of the experimental microgrid is shown in Fig. 2.

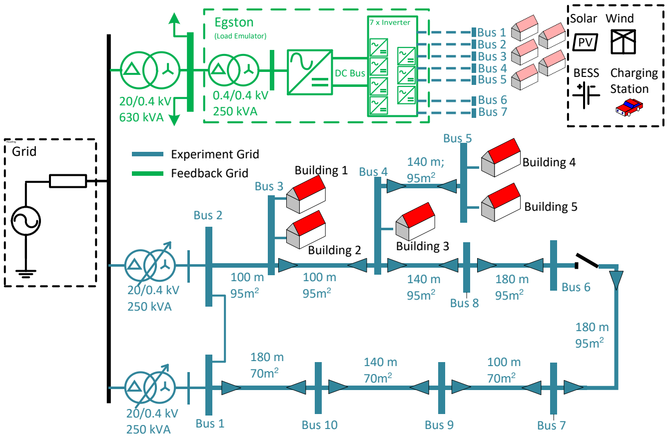
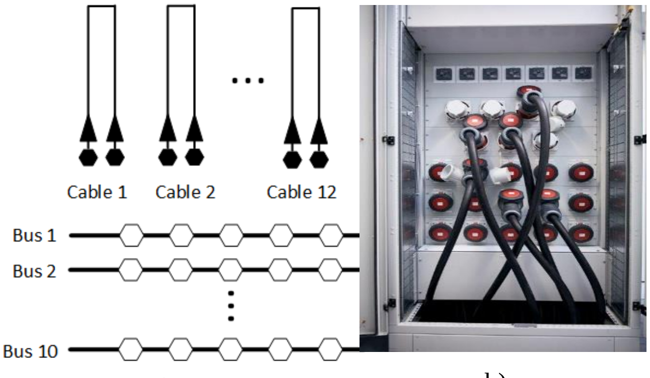


Fig. 2 Electric Grid Single Line Diagram

Medium voltage (20 kV) feeder supplies the experimental microgrid system. Two OLTC transformers (250 KVA each) are supplying the laboratory experimental grid that consists of maximum 10 low voltage (LV) buses. The topology of the LV grid is formed by connecting these 10 LV buses with 12 available cables that are laid in the foundations of the building. The total length of all cables is around 1.8 km, with individual lengths between 100 m and 250 m and conductor (copper) diameter between 70 and 150 mm^2. The cables' endings are accessible at the switchboard (Fig. 3) where they can be connected to any of the 10 LV buses, which makes the realization of an arbitrary microgrid topology possible.



a) b)

Fig. 3 LV Switchboard for grid reconfiguration a) Schematic view, b) Photo

In addition to the cables that form the topology of the experiment grid, several electrical components are available in the laboratory, which can be connected to any of the 10 LV buses:

- Electric Batteries (2 x 13 kWh and planned extension with additional 100 kWh)
- Photovoltaic panels (18 kWp). These solar panels are mounted on the building roof.
- Synchrounous and induction motor/generator emulator (30 kW each). This is achieved by the motor/generator block, where the motor is controlled by an industrial inverter and provides desired torque to the experimental machine.
- 2 x EV charging station. EV charging stations are located at the parking lot in front of the building.
- Prototype 4 leg inverter (under construction)
- Egston prosumer emulator [7]

The photos of the Egston prosumer emulator, solar panels and EV charging stations are shown in Fig. 4.

a) *b)* *c)*

Fig. 4 Photos of the laboratory equipment. a) Egston load emulator; b) solar panels; c) EV charging stations

The Egston load emulator [7] consists of a transformer (galvanic isolation), rectifier, DC bus and 7 three phase bipolar inverters connected to the common DC bus. A bipolar inverter represents a fully controllable load/generation with the maximum current of 126 A and voltage of 433 V. Five out 7 inverters are used as 5 buildings prosumers. Other 2 inverters are used as additional load/generation that can be connected to arbitrary LV bus, normally used to emulate additional renewable resources located outside of the buildings.

The concept of circulating power is accomplished through a feedback grid that is supplied through the 630 kVA transformer.

The feedback grid supplies Egston load emulator and auxiliary equipment that is not part of the experimental grid.

B. *Electric system of a building*

As mentioned above, the experimental system consists of 5 buildings and the grid that connect them. Each of these buildings is emulated as a composite load through parallel connection of Egston inverter, solar panel, battery and several electric outlets that can supply arbitrary household appliance as shown in Fig. 5.

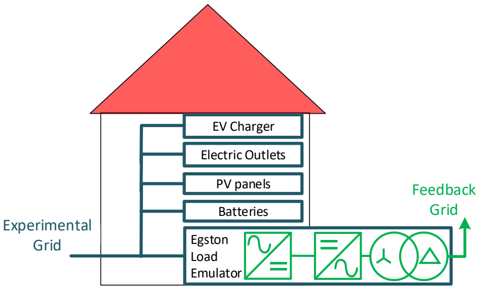


Fig. 5 Electric System of a Building

IV. HEAT SYSTEM

A. *Heat distribuiton grid*

A two and three temperature level bidirectional heat grid connects 5 buildings, where each of the buildings is capable of taking the role of heat sink or source, i.e. to behave as a heat energy prosumer. Three buildings are connected by a three temperature level heat grid that provides flexibility to emulate heating and cooling systems or to supply heating with two different temperature levels.

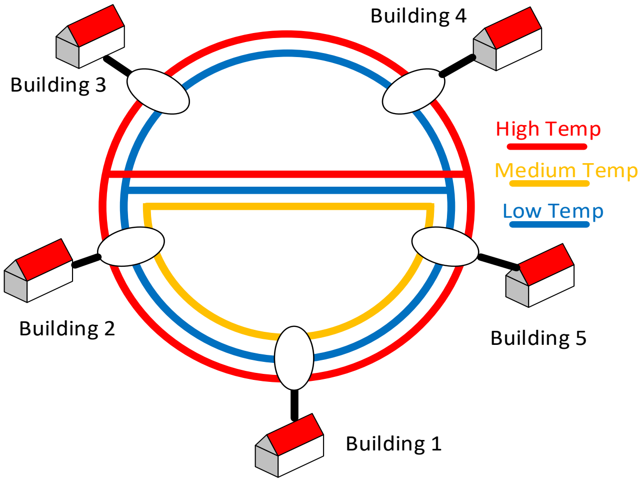


Fig. 6 Emulated heat grid with two and three temperature levels

The base heat grid topology is given in Fig. 6, with the possibility of reconfiguration to other topologies with limited efforts.

In order to avoid long pipe systems, special modules are inserted to emulate dynamic behavior of the arbitrarily long pipes. These modules introduce controlled delay in the hot water flow, which is accomplished with appropriate cooling or heating of the flowing water (depending on the heat flow change).

B. *Heat house model*

The buildings are equipped with different heat modules that enable various experiments with the heat system. The overview of the equipment is given in the TABLE 1, whereas the principal scheme of the building heat system, photos of the heat modules and a CHP are given in Fig. 7, Fig. 8 and Fig. 9, respectively.

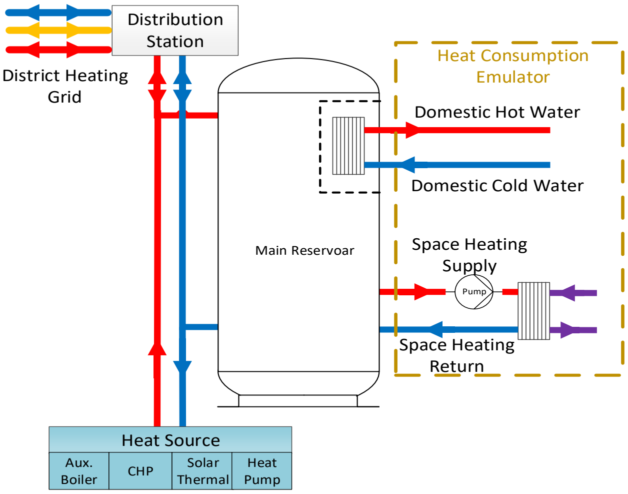


Fig. 7 Emulated heat system of a building

Fig. 8 Building 1 heat modules

Fig. 9 CHP of Building 5

The central component in the house heat system is the hot water storage, which is heated from different sources (District Heating Grid, Heat Pumps, Boilers, Solar Thermal Sources or CHPs). The clean domestic hot water is obtained through the Domestic Hot Water element (a heat exchanger with or without a storage). The amount of consumed hot domestic water is regulated through the valves, after which the water is spilled. The space heating consumption is emulated through the regulated heat exchangers that is cooling hot water to the extent that replicates the desired space temperature. This emulated temperature drop in the heat sink (space heating emulator) is determined through the simulation of the building heat dynamics. The building model is developed using Modelica language in SimulaitonX and its Green City libarary [8].

TABLE 1 OVERVIEW OF HEAT MODULES

	Building 1	**Building 2**	**Building 3**	**Building 4**	**Building 5**
CHP	Gas 2kW$_{el}$, 5,2kW$_{th}$	None	None	Stirlingengine, 1kW$_{el}$, 6kW$_{th}$	Gas 5kW$_{el}$, 11,9kW$_{th}$ Gas 18kW$_{el}$, 34kW$_{th}$
Aux. Boiler	Condensing boiler, 20kW$_{th}$	Condensing boiler, 20kW$_{th}$	None	integrated in the CHP, 20kW$_{th}$	Condensing boiler, 50kW$_{th}$
Heat Pump	None	Airsource HP, 10kW$_{th}$	Brinesource HP, 10kW$_{th}$	-----	-----
Solar thermal source (el. heater)	9 kW$_{th}$	9 kW$_{th}$	9 kW$_{th}$	-----	-----
Hot water storage	800 liters	800 liters	1000 liters	1000 liters	2000 liters
Domestic Hot Water	Storage: 500 l	Fresh Water Station	Fresh Water Station	Combistorage	Fresh Water Station
Heat Sink	30 kW$_{th}$	30 kW$_{th}$	30 kW$_{th}$	30 kW$_{th}$	60 kW$_{th}$
Distribution Unit	30 kW$_{th}$	30 kW$_{th}$	30 kW$_{th}$	30 kW$_{th}$	60 kW$_{th}$
Booster Heat Pump Distribution Unit	19 kW heat 14 kW cold	-----	-----	-----	-----

V. MONITORING AND CONTROL SYSTEM

The equipment described in the previous paragraphs represents the core of the laboratory design, however the control and monitoring system allows for flexible and efficient utilization, which is essential for a successful research platform.

The lab control and monitoring system is based on the National Instruments [9] PXI systems and VeriStand software for building and deploying Software-in-the-Loop (SIL), Model-In-the-Loop (MIL) and Hardware-In-the-Loop (HIL) solutions. The control and monitoring architecture is given in Fig. 10. Three workstations with NI VeriStand software are available and used to program any controller in the system. It is important to note that it is not necessary to run lab experiments on the full system, instead a subset of the available controllers (and associated hard-ware) can be used independently from the remaining system.

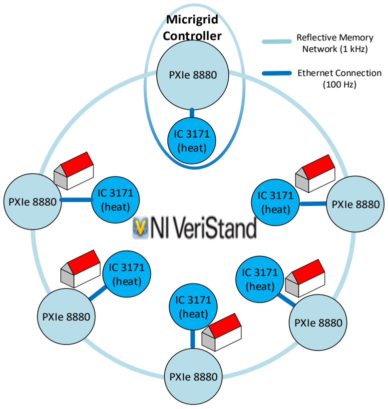


Fig. 10 Control and Monitoring Architecture

Each building and the microgrid control center have two controllers, one NI PXIe 8880 for electric system, and one industrial controller NI IC 3171. These controllers operate at 10 kHz and 1 kHz rate, respectively. The telecommunication grid consists of a ring that operate at 1 kHz rate. Reflective memory technology is employed for linking the real-time targets using the GE 5565 reflective memory cards. This ensures that all measured data is available to each controller. The industrial controllers communicate with corresponding PXIe systems through Ethernet cable at 100 Hz rate.

In addition to playing the role of controllers in the experimental microgrid, NI PXIe systems are powerful enough to operate as a real time simulator, enabling SIL, MIL and HIL experiments. Once the solution is tested with simulated models, it can be validated in the Hardware-In-the-Loop or Physical Test configuration.

NI VeriStand software, which implements the V-Model of development, enables seamless transition from the simulation to fully hardware environment. This is accomplished through the standardized NI VeriStand interface (signals) between different models, which replicates the real-life interfaces. Therefore, if the simulation model interfaces are defined to correspond to the hardware interfaces (control inputs, measured signals, etc.), the transition to the Physical Test configuration consists of only reassigning the interfaces to the real life signals in I/O cards.

NI VeriStand is able to load any compiled models, which enables the use of different model development tools such as MATLAB®, Simulink, LabVIEW, and .NET languages. In addition, NI VeriStand can be controlled through the NI VeriStand .NET API.

A. *Central Monitoring System*

NI VeriStand's UI Manager enables custom-built visualization and control of the real-time system. The user interface developed in the CoSES laboratory monitors all important variables such as electric and heat energy flows in the grid and in the individual building. The examples of developed user interfaces are shown in Fig. 11 and Fig. 12.

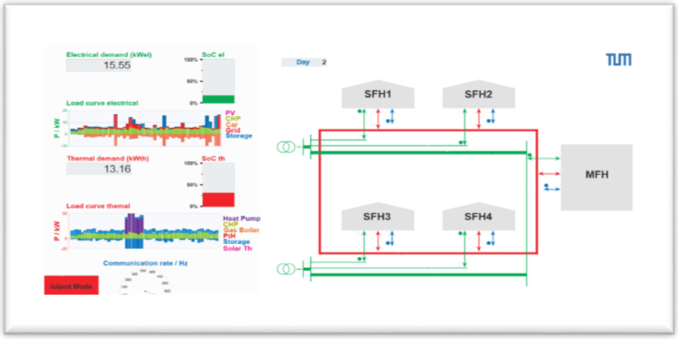


Fig. 11 User Interface for overall monitoring of the lab microgrid

SFH3

P_demand (kW) 0.916642

P_demand (kWth) 0.134054

Lost comms packet 0

P_Photovoltaik (kW) 0.770625

P_Solar (kWth) 0.134054

P_EV (kW) 0

P_Heatpump (kWth) 0

P_Grid (kW) 0

P_Gasheater (kWth) 0

P_Battery (kW) 0.146017

P_Heat_storage (kWth) 0

Fig. 12 User Interface for monitoring of a building consumption

B. *Weather Station*

In order to gain insight in the available solar and wind energy resources at the site, a weather station is installed on the rooftop. The weather station has a sun tracker, diffused radiation measurements, wind speed and temperature measurements. The measured data are processed in the Arduino microcontroller and stored in a SQL database with 5 sec resolution. The overview of the weather data is published on the Apache hosted website and linked an app via Weewx protocol.

VI. RESEARCH POTENTIALS

The main research direction behind the CoSES laboratory is the investigation and validation of the sector coupling (electricity and heat) within the microgrid concept. In particular, the following challenges of the future smart energy systems will be studied:

- Development of suitable models of integrated energy systems that need to be validated with a real life equipment.
- Proposing economically viable electric and heat systems that enable bidirectional flows and consequently free movement of energy.
- Implementation of appropriate amount of coupling components such as heat pumps, CHPs, and EVs to exploit the available flexibilities in a synchronized manner.
- Intensive utilization of ICT and power electronics platforms that enables sufficient observability and controllability of the system with reasonable costs while respecting the data privacy.

VII. CONSIDERATIONS IN CONSTRUCTING THE LABORATORY

Designing and constructing a laboratory like CoSES requires a multidisciplinary approach and coordination between many stakeholders, which imposes additional complexity. The top priority is given to the safety of personnel, not only during the construction phase but also during the planned operation. For that reason, a separated control room is constructed to eliminate the need of staying in a main hall during experiments. In addition, separated rooms for power electronics converters and batteries is designed with special air conditioning system in order to localize any potential accidents related to this equipment. MV equipment is located in a part of the building where only trained staff is able to enter.

A particular challenge was a construction of modules with specific requirements that are not available as commercial products. For that reason, many parts of the laboratory had to be developed in-house with the help of graduate and undergraduate students.

VIII. CONCLUSIONS

Even though theoretical solutions to exploit synergy of different energy systems have been reported in the literature, it is necessary to create multidisciplinary laboratories where these solutions can be validated and tested. The paper presents a CoSES laboratory facility at TU Munich that is aiming in addressing this need. The adopted architecture of the facility enables easy reconfiguration and consequently possibility of doing research in wide range of topics related to microgrids concept in integrated energy systems. It is expected that the developed laboratory will be a valuable asset in developing techno-economically feasible technical solutions as well as in teaching of a new generation of engineers with hands on experience in complex multidisciplinary systems.

ACKNOWLEDGMENT

The Deutsche Forschungsgemeinschaft (DFG) and Bavarian Government have financed the development of the laboratory. We acknowledge the support of TUM professors who participated in the lab design phase. The authors are grateful to a large number of students who invested a lot time and effort in building the lab. We acknowledge support from NI in designing the control and monitoring system.

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