INNOVATIVE HEAT STORAGE MANAGEMENT BY OBJECT ORIENTED CONTROL

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ABSTRACT

The Institute for Energy Economy and Application Technology (IfE) has developed a temperature measurement setup and a mathematical methodology to calculate the thermal balance of thermal storages continuously. Any variation of temperature gradients depends on load modulation of heat generators or heat demand. A developed piston stroke model (displacement of hot or cold water) describes the thermal balance enough adequate to know the object (residential building) status. With the help of this Object Oriented Control, thermal powers, the useful thermal energy content for heating purposes and the available thermal storage capacity can be calculated.

The Object Oriented Control is operated by the Innovative Heat Storage Management. This management of the system "micro-CHP-unit and thermal storage" can prevent grid stability problems of distributed power generation, due to detailed knowledge of the object status and enables object oriented micro-CHP heat and power generation (maximization of on-site power generation). The Innovative Heat Storage Management optimizes the usage of the thermal storage capacity to modulate the electric power under consideration of the heat demand coverage and grid influences. The thermal storage becomes a controllable and active component within the heating system.

MOTIVATION AND INTRODUCTION

Combined Heat and Power (CHP) can contribute to resource conservation within the next decades and therefore, distributed power generation by residential micro-CHP units in the range up to 10 kW_{el} could expand significantly. Heating systems (HS), which consist of micro-CHP unit, peak load boiler (PLB) and thermal storage, will supply residential buildings and will change today's distribution networks. Heat led operating micro-CHP units can be added to distributed power generation technologies, which depend on ambient conditions (ambient temperature, solar irradiation). Residential buildings will show a "fluctuating" residual load profile of electricity consumption and feed-in, which could cause grid stability problems. Innovative Heat Storage Management by Object Oriented Control can decouple power generation and heat demand of distributed micro-CHP units temporarily to prevent a "fluctuating" residential residual load and form a net-friendly characteristic.

Energy Demands and Technical Building Services

The evaluated residential building is a multi-family house (MFH) with 10 flats and 22 occupants. It is based on the German building classification of the Institut Wohnen und Umwelt (IWU) and located in Munich. The residential building was renovated under conditions of the energy saving regulation in 2002. [2]

The thermal and electric energy demand of the residential building is defined by five so-called type days, which provide the calculation of annual energy balances. These type days represent the spectrum of ambient conditions of the test reference year (TRY) of Deutscher Wetterdienst (DWD), which is used to simulate the heat demand considering the parameter of the building classification of IWU. The heat demands of all type days have dedicated electricity and domestic hot water demands. The electricity demand refers to the reference load profiles of single- and multi-family houses with micro-CHP units of the Verein Deutscher Ingenieure (VDI). The domestic hot water (DHW) demand is defined as normal day tap profile. The residential building's energy demands of one transition day are shown in ***Figure 1***. [2]

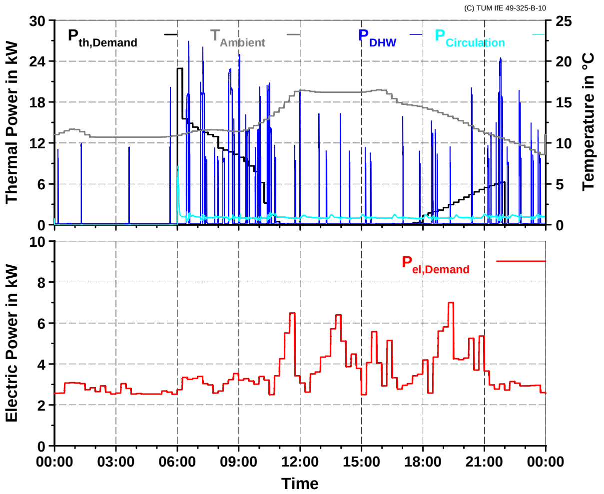

Figure 1: Building's Energy Demand

The public electric grid and the natural gas net supplies the residential building. The heating system consists of a micro-CHP unit, a peak load boiler, a thermal storage (2000 l) and a domestic hot water tank (500 l). The micro-CHP unit provides 24 % of the thermal peak load. The peak load boiler covers the remaining heat demand.

The installed modulating micro-CHP unit has a rated electric power of 4.5 kW_{el}, a rated thermal power of 12.5 kW_{th} and operates grid-connected. The used modulating natural gas condensing boiler has a rated thermal power of 45.0 kW_{th}. [2]

Today's Control of Heating Systems

Micro-CHP and heating system controls are often based on three heat storage sensors with set temperatures and detect only a completely full or an empty thermal storage by a characteristic hysteresis curve. Thermal storages are compensating components and balance only surplus heat.
In general the thermal load is not measurable. It depends on the ambient conditions and the domestic hot water demand. To detect the thermal state of a residential building, the thermal storage temperatures, the present thermal storage capacity and the thermal balance (sum of heat generation and heat demand) have to be known.
The electric load of a building is usually not included in heating system controls. It can be measured by a smart meter, which has an impulse interface. The meters' output is an impulse signal, which depends on the current electric load status. Some of today's micro-CHP units have usable impulse interfaces and are able to run with the help of this input data.

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OBJECT ORIENTED CONTROL

The Institute for Energy Economy and Application Technology has developed a temperature measurement setup and a mathematical methodology to calculate the thermal balance of thermal storages continuously. Furthermore, the thermal energy content, the thermal storage capacity and management time slots are definable and with the help of this Object Oriented Control an Innovative Heat Storage Management is realizable.

Approach

Object Oriented Control considers the thermal balance (current thermal conditions) to maximize micro-CHP on-site power generation and to prevent grid influences. The approach is based on a robust, common and easy retrofit temperature measurement. The mathematical methodology determines a temperature profile of the thermal storage using the temperature sensors. ***Figure 2*** shows the measured temperature profile at time t_0 and t_1 as graphically interpolated black dots. The temperate profile can be adapted as sigmoid graph to represent the characteristics of the thermal storage temperatures. The red graphs in ***Figure 2*** show that the temperature characteristics are well approximated. The application of sigmoid graphs results in continuous and differentiable graphs of measured storage temperature characteristics. [1]

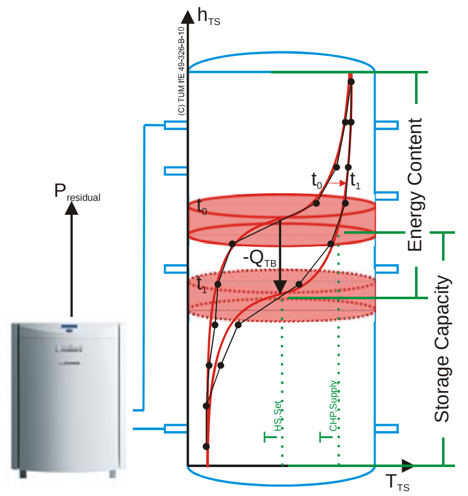

Figure 2: Approach of Object Oriented Control

A detectable mixed water zone is formed, due to the temperature-dependent density of water. The mixed zone is characterised by an endless temperature gradient greater than zero and is formed between upper limit temperature (supply temperature of the heat generators) and lower limit temperature (return temperature of the heat sinks) and stays nearly unmodified over the day. The mixed zone moves up- and downward and displaces hot, respectively cold water. It represents a piston within the thermal storage (shown in ***Figure 2*** as red cylinder). The so-called piston stroke model describes the thermal balance enough adequate to know the object (residential building) status continuously. Here, the thermal storage is discharged between t_0 and t_1 and the mixed zone moves downwards. Otherwise, thermal storage charge processes will move the mixed zone upwards. [1]

Calculation of Thermal Balance

Main task of the described model is the calculation of the thermal balance in order to enable an Object Oriented Control. Within the first step, a time interval Δt has to be defined, which enables the recognition of thermal storage differences without a significant response rate reduction of the Object Oriented Control. The second step is the detection of the height Δh_{TS} of the inflexion point of the sigmoid graph (centre of the mixed zone) at the beginning and at the end of each time interval. Therewith the direction of the mixed zone movement and the difference of heights in the defined time interval can be calculated. Thermal storage cross section area A_{TS}, the difference of upper and lower thermal storage temperature $(\vartheta_S - \vartheta_R)$ and the thermal capacity of water result in an average thermal power, the thermal balance $\dot{Q}_{TB}$. Equation (1) describes the mathematical context within the defined time interval.

$$\dot{Q}_{TB} = \frac{A_{TS} \cdot \Delta h_{TS}}{\Delta t} \cdot \rho \cdot cp \cdot (\vartheta_S - \vartheta_R) \qquad (1)$$

$$\dot{Q}_{TB} = \dot{Q}_{CHP} + \dot{Q}_{PLB} - \dot{Q}_{Demand}$$

Varying heat demand, domestic hot water tank charges and peaks of the heat generators cause high fluctuations of the thermal power. The calculated thermal balance demonstrates high accuracy and wide operability of piston stroke model, sigmoid graph adaptation and calculation model. [1]

Management Time Slot

Additional to the current thermal balance of charge and discharge power, the usable thermal energy content and the available thermal storage capacity are calculated. The thermal energy content for space heating depends on the set temperature $T_{HS,Set}$ of the used heating curve. The utilizable thermal storage capacity is defined by the supply temperature of the heat generators $T_{CHP,Supply}$. All important parameters to calculate the thermal energy content and the thermal storage capacity are also shown in ***Figure 2*** as green temperatures and green thermal storage parts.
If quasi-stationary micro-CHP operation is assumed, the division of the thermal energy content, respectively the thermal storage capacity, by the calculated thermal balance, results in a time slot, which describes a possible charge or discharge time.
This precise knowledge of the decoupling management time slot of thermal energy demand and thermal energy generation defines the degree of freedom for the optimized micro-CHP unit operation with thermal storages. The micro-CHP or heating control can adjust the heat and power generation at an early stage and this is essential for the developed Innovative Heat Storage Management.

INNOVATIVE HEAT STORAGE MANAGEMENT

The Object Oriented Control, based on the thermal balance model, enables the development of the Innovative Heat Storage Management, which allows an optimized operation of micro-CHP units in residential buildings.
The Object Oriented Control is operated by the Innovative Heat Storage Management. This management of the system "micro-CHP-unit and thermal storage" can prevent grid stability problems of distributed power generation, due to detailed knowledge of the object status and enables object oriented micro-CHP heat and power generation. The Innovative Heat Storage Management optimizes the usage of the thermal storage capacity to start/stop (or modulate) the electric power under consideration of the heat demand coverage to maximize the on-site power generation and to prevent grid influences. The thermal storage becomes a controllable and active component within the heating system.

Approach and Feedback Control System

The developed Innovative Heat Storage Management knows the residential energy demands for the first time. The smart meter output combined with the thermal balance enable a power led operation, due to the continuous feedback control of the thermal storage capacity and the thermal storage energy content.
The developed feedback control system consists of a cascade control with two control circuits and is shown in ***Figure 3***. The first control is related to power led operation and is the faster control circuit. The second control adjusts the thermal power generation to the residential heat requirements. Any variation of electrical power results in a variation of the thermal balance. The impact of the power led operation to the heat demand coverage is regarded within the thermal balance. Considering thermal storage capacity and thermal storage energy content, result in the management time slot. Depending on the current thermal balance, the thermal control system adjusts the thermal power of the micro-CHP unit (temporarily heat led operation) and in case of high thermal demands, the PLB will be enabled.

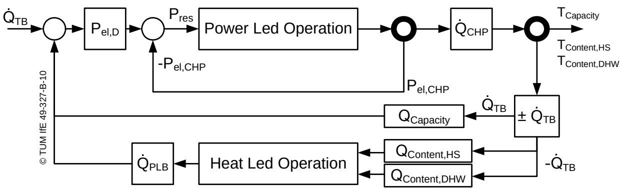

Figure 3: Feedback Control System of the Innovative Heat Storage Management

The Innovative Heat Storage Management implements the Object Oriented Control to optimize heat and power generation. The on-site power generation will be maximized and therewith, the electricity purchase will be minimized.

Control and Management

The application area of the Innovative Heat Storage Management is separated in three main parts. The thermal balance indicates the approval management time slot and defines the valid feedback control. The management parts and the dependencies of thermal balance, thermal storage capacity and storage energy content as well as micro-CHP unit power generation are described in ***Figure 4***.

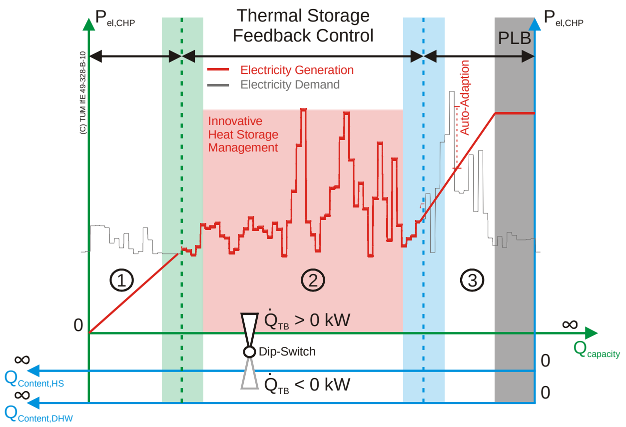

Figure 4: Innovative Heat Storage Management

The first part is defined by a thermal storage charge (positive thermal balance) and a low thermal storage capacity. The micro-CHP unit will decrease the electrical power output, although the electricity demand is high. If the electricity demand drops down to lower values than the Innovative Heat Storage Management has calculated, the control switches back to power led operation.

The second part is characterised by sufficient management time slots (for charge as well as discharge processes) and correspond to power led operation. Variations of thermal demand or generation will be detected by the thermal balance. Any changes in operation conditions (reduction of management time slot) will be recognized by the developed feedback control and adapted by the Innovative Heat Storage Management. In case of a positive thermal balance (thermal storage charge) and a significant management time slot, due to high thermal storage capacity, the micro-CHP unit runs power led. Negative thermal balance and adequate energy capacity means power led operation until the energy capacity is low and the management switches to heat led operation.

The third part covers the operation conditions with high thermal demand. Thermal Storage discharge (negative thermal balance) and low thermal storage energy content result in an increasing micro-CHP power, if necessary, up to the rated electric and thermal power. Therewith, electricity could be feed in, but in case of high electricity demand, the power generation will be adapted to the demand to increase the on-site generation. Thermal peak loads will be covered by the PLB.

Experimental Results

Object Oriented Control and Innovative Heat Storage Management were verified by test bed experiments. ***Figure 5*** shows the measured results of the above described transition day with standard micro-CHP control (upper diagram) and Innovative Heat Storage Management (lower diagram).

The operability of the developed management is proved within the experimental analysis. Due to the high accuracy of the thermal balance model and the implemented management, the heat demand is covered monovalent with simultaneous consideration of the electricity demand. Substantial characteristic in the lower diagram is the on-site power generation in time of high electricity demand. Due to the thermal storage, the heat generation is decoupled from heat demand. At the morning, the thermal storage is used to cover the heat demand and at noon it is used to maximize the on-site power generation. The operation of the micro-CHP unit is shifted to hours with high electricity demand and therewith, on-site generation is maximised and grid influences are minimized.

It can be seen, that for the standard operation (upper diagram), the micro-CHP runs heat led. The building's electricity demand is not considered and thus the on-site generation is lower, compared to the Innovate Heat Storage Management.

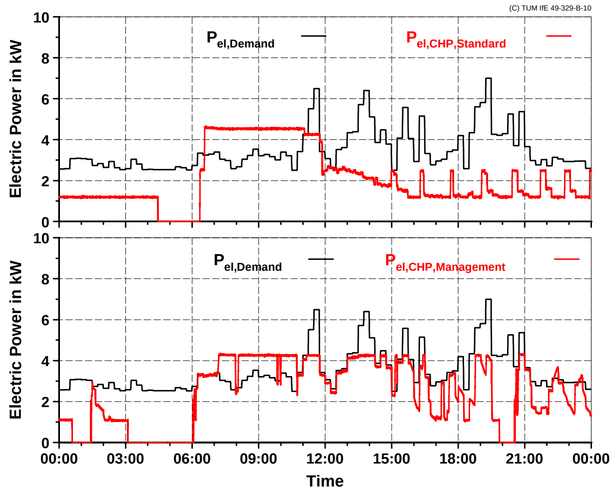

Figure 5: Experimental Results of the Innovative Heat Storage Management by Object Oriented Operation

CONCLUSION

Object Oriented Control enables a building control under consideration of all kind of energy demands for the first time. It is integrated within the Innovative Heat Storage Management, which optimizes the combination of micro-CHP unit operation and thermal storage usage to form distribution network friendly micro-CHP operation. This management maximizes on-site power generation, can be used in case of future flexible electricity tariffs and can be the central component of a virtual power plant.

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