Demand Response with Functional Buildings using simplified Process Models

Peter Palensky *Senior Member, IEEE*,
Gerhard Zucker *Senior Member, IEEE*,
Florian Judex, and Reiner Braun
Austrian Institute of Technology
Energy Department
{peter.palensky, gerhard.zucker, florian.judex, reiner.braun}@ait.ac.at

Friederich Kupzog *Member, IEEE*,
Thomas Gamauf *Graduate Student Member, IEEE*,
and Jan Haase *Senior Member, IEEE*
Institute of Computer Technology
Vienna University of Technology
{kupzog, gamauf, haase}@ict.tuwien.ac.at

***Abstract*—Smart Grids ideally interconnect intelligent grid members. One big share of grid presence is with buildings. Flexible and grid-friendly buildings would improve grid management and are an important contribution to the integration of renewable energy sources. Classical buildings, however, are passive and not cooperative. This article describes how electro-thermal processes in buildings can be used for demand response and how such intelligent behavior can be enabled via communication technology. Experiments and simulations on typical mid-European buildings were done to estimate the potential time constants.**

I. MOTIVATION

Buildings are responsible for around forty percent of an economy's energy consumption in western countries [1]. To reach the given emission goals an obvious way is to increase the building's energy efficiency. Typical measures are improved building shell (insulation) or more efficient HVAC (heating, ventilation and air conditioning) equipment. Such efficiency measures immediately and directly reduce the overall energy demand and its related emissions. The typical development – especially observable in the European Union – is to increase efficiency to the maximum (a.k.a. Passive House Level) and in addition to add local renewable energy generation (e.g. photovoltaics, solar thermal, wind, ground water) to cover the remaining energy demand or to even reach "plus-energy" level. In the latter case, the building would generate a positive net energy balance, i.e. generate more than it needs.

This positive net energy balance is not to be confused with energy autonomy, since the building is still grid-connected (electric, thermal) and dynamically changes between its roles as energy producer and energy consumer. Local, as well as centralized, renewable energy often has a stochastic behavior: it feeds in whenever the primary resource (solar radiation, wind) is available. By the use of a good prognosis, flexible conventional generation (gas turbine power stations) and potential storage (pump storage power plants) it is possible to keep these fluctuations under control. However, the increasing share of renewable generation and the approaching wave of electric vehicles with its thirst for electricity pose new challenges for our energy system and its generation, transport and distribution capacity.

Intelligent buildings can help. "Intelligence" in this context means that the building is equipped with an advanced building automation system (BAS) that

- influences energy-relevant equipment and settings like HVAC or windows,
- senses energy-relevant information like occupancy, weather, or usage, and that
- contains advanced control algorithms that go beyond plain PID (proportional, integral and derivative control function).

Such an advanced BAS can use weather forecasts, learn usage profiles or reschedule the operations of building systems in order to meet smart grid requirements (see [2] and [3]). One key ingredient for operating in such a smart way is to know the dynamic behavior of the building. Model-based control needs such a building model to determine the optimal control strategy. Unfortunately, existing simulation methods and tools are computationally very costly and therefore not suitable for a standard embedded building controller. We describe how this can be solved.

II. METHODOLOGY

Current control strategies for building automation consider the electric grid as a permanent source of energy, which does not constrain consumption at any time. While this still holds true most of the time it is predictable that the situation will change based on two factors: increasing energy consumption and integration of renewable energy sources like photovoltaic systems, wind turbines or combine heat and power plants (CHP). The future goals of a BAS must include the optimization of consumptions towards the electric grid, i. e. reduction of energy consumption during peak load times. This is one of the goals of Demand Side Management (DSM). More general, DSM aims at modifying the electric demand at the consumer side by influencing user behavior or modifying schedules of energy consuming systems. Shifting consumption away from peak load times into off-peak periods is a benefit for the electric grid, which has to be dimensioned for maximum load. The building is by itself well suited to act as a storage for thermal energy in two ways: first, energy is stored in the building structure itself (walls, floors, ceilings, and envelope as well as the inventory). Second, the energy systems in the building typically contain storages e.g. tanks for hot water used for heating and tap water, which are also accessible by the BAS. Thermal energy stored in a building is influenced by HVAC systems using means for heating or cooling and regulating air exchange by ventilation. Furthermore, HVAC accounts for almost half of the overall energy consumption in buildings [4] and is thus the main energy consumer. Influencing the temperature is the least noticeable modification to human users. Modifying air exchanges rates is more critical, since indoor air quality rapidly decreases (CO2 increases) when the ventilation system is switched off. Still, ventilation as well as heating and cooling carry the biggest potential for demand side management in buildings. Many approaches exist that consider applying DSM to white goods and consumer electronics. While systems like refrigerators or dishwashers do contain a certain electric and thermal load shifting potential, existing building automation does not provide feasible means to control these devices in a way that does not harm the device (by e.g. forced power supply cut-off during normal operation) and does not affect the comfort requirements of the human user.

For a DSM system to be successful the human comfort of the users is an important constraint that needs to be considered. Violations of human comfort by exceeding boundaries in temperature, humidity or air quality have to be avoided by the BAS. Guidelines for maintaining comfortable indoor conditions are provided by ASHRAE [5].

Using themal storage for electric demand side management requires coupling between two types of energy. Ventilation provides straight forward coupling and can be accessed by the BAS directly (under the above mentioned constraints of air quality degradation). Certain heating systems also provide appropriate coupling; these are heat pumps, CHPs and direct and night-storage heaters.

Load shifting can be achieved on two levels:

- instantaneous: the BAS instantly switches off as many loads as possible for a feasible time period
- scheduled: given that the expected load profile is known, the BAS can preheat or pre-cool the building right until before the load shifting period

In both cases a model of the building is needed, which contains the thermal behavior of building and HVAC systems. The output of this model is an operation schedule for HVAC systems in order to meet the required profile. It is possible in the first case that such a model is not part of the system, but rather the necessary parameters are derived empirically or are based on expert know-how. In this case, the maximum load shedding period is defined a priori and not modified. For more detailed DSM and especially for predictions it is necessary that the BAS has access to a thermal model of the building and its systems, which allows to calculate preheating times and maximum load shedding periods.

While DSM in buildings supports the electric grid, it does not actually save energy in the building. Only when the system boundaries are extended to a more global perspective, it becomes clear that the benefits lie in a more robust grid and the possibility to postpone building additional or stronger supply lines. Within the building the shifting of load thus means that energy, which is not consumed during peak load times is consumed at other times — either after the peak load period or (if load shedding can be scheduled) before. This rebound effect has to be considered when planning load shifting; in the worst case all consumers are shifted away from the peak load just to create another peak immediately after the original period.

The system that is described in this paper relies on a regular building automation system (BAS) that is augmented with an additional component responsible for handling DSM - the building agent. Each building has an agent, which all communicate with a central smart grid controller. The controller is responsible for issuing load shedding requests, either instantaneous or scheduled. A building agent reacts on such requests by using its built in thermal model of systems and building to estimate the on and off times of HVAC components. The thermal model shall be capable of representing the necessary thermal properties, but need not be too advanced. A complete thermal simulation of building and systems would be an oversized approach, given that the models need to be created for each building. A solution that requires less work force to enable prediction is sufficient and is described in the next section.

III. PROCESS MODELING

Building automation systems (BAS) today are based on linear control theory implementing P, PI, and PID controllers (i.e. using proportional, integral and differential parts of the input signal) in the field level or even simpler on-off controllers. Information technology has pushed forward the automation and management level, resulting in a broad variety of BAS from different vendors covering all issues including control, monitoring, reporting, and maintenance for various application areas like indoor climate, lighting, security, and safety of persons and buildings. The control mechanisms are composed of a combination of linear control with digital control. A typical control strategy of a system (e.g. a heat pump) defines operation states that are changed based on input values. The implementation of such a control strategy is either done in a programming language or graphically by composing the control strategy out of predefined function blocks. The programmer has to place the blocks (which also include the linear controllers) and connect inputs and outputs. This graphical solution simplifies commissioning, since it is not necessary to debug the control strategy down to the level of single commands (as is necessary with programs). Model-based control (MBC) has not yet penetrated the market, although research is proving benefits from this advanced approach. Currently robustness is the strongest argument for traditional controls: maintenance is costly and outweighs the energy losses due to suboptimal systems. This may change soon based on awareness for energy efficiency and increasing energy costs.

Due to the fact that detailed thermal simulation is not an option, as the best case solution presented in this paper is applied to all building in a grid, the process model for the MBC has to be reasonably simple. The heat flux Q within a building can be described by the losses Q_{loss} and gains Q_{source}:

$$\dot{Q} = Q_{loss} - Q_{source} \tag{1}$$

Under the assumption that the room air and the wall temperature are nearly equal, the equation can be reformulated for temperature using $T = \frac{Q}{c_p m}$, where c_p is the thermal capacity of the walls, and m their mass. For $Q_{source} \equiv 0$, the solution is

$$T_{building} = (T_{set} - T_{out}) \cdot e^{\left(-\frac{t}{\tau_{cool}}\right)} + T_{out}, \tag{2}$$

giving the cooling behaviour of a building starting from temperature T_{set} (usually the setpoint for the heating system) to an outside temperature $T_{out} < T_{set}$. For a large enough Q_{source}, there is a theoretical equilibrium temperature $T_{end} > T_{out}$ which will be reached eventually, leading to the solution

$$T_{building} = (T_{end} - T_{set}) \cdot \left(1 - e^{\left(-\frac{t}{\tau_{heat}}\right)}\right) + T_{set}. \tag{3}$$

The values τ_{cool} and τ_{heat} are values which depend on the building itself, but also on

- the air exchange rate,
- T_{out} and
- Q_{source}, composed of internal gains and the actual heating system.

All these values can be assumed to be constant for certain time periods, allowing the construction of the behavior of the building by joining equations 2 and 3 piecewise in time. Furthermore, the values of the other parameters can be restricted to a set of scenarios, e.g. assuming only certain air exchange rates or internal gains based on the main types of usage of a building, which will lead to a set of time constants for each building. As U-value, thermal mass and the ratio between volume and surface of the building can be accurately estimated at least for predominant building types in a region, BAS manufacturers or vendors can anticipate possible buildings by doing an exhaustive search using a building simulation software (e.g. TRNSYS or Energy+), and fitting the parameters of equations 2 and 3 to the results of these simulation. For a given building, the set of time constants will then be selected from this pool of results.

For buildings which do not have a heating system which is independent of the domestic hot water (DHW) further simple process models are needed to be able to use all the systems for an increased flexibility towards the grid. The most important components are an electric heat source (heat pump, combined heat and power, etc.) and a hot water storage tank, which supplies both the heating system and the DHW. As the heating power Q_{source} supplied by the heat source is known, as well as the supply and return temperatures of the heating system, and the temperature loss in the tank is negligible for the time scale, the only unknown influence is the energy consumption due to DHW. Using standard values for DWH profiles, e.g. the "ASHRAE draw profile" [6], which also give draw rates that are constant for certain time periods, and computing the energies

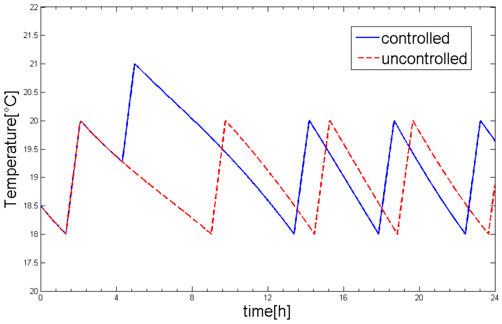

Fig. 1. Building agent shifting heating load by preheating a building

$$Q_{heat} = cp_{H_2O} \dot{m}_{heat} \Delta T_{heat} \tag{4}$$

and

$$Q_{DWH} = cp_{H_2O} \dot{m}_{DHW} \Delta T_{DHW} \tag{5}$$

used for heating and DWH, the equation for the energy flow out of and into the storage tank can be simply given as

$$\dot{E}_{tank} = Q_{source} - Q_{heat} - Q_{DHW}, \tag{6}$$

in which the right hand side can again be assumed as constant for time periods, enabling the to give a piecewise linear behavior for the hot water tank.

At the time of the set-up of the building agent at the BAS, the appropriate look up tables for the parameters τ_{cool} and τ_{heat} have to be selected, and the electrical consumption of the heating system has to be supplied. In more complex systems, the capacity of the tank, and the energy consumptions of the systems would also have to be specified at this point. As the building agent has to be connected to the BAS, it can be assumed that the standard mode of operation in terms of setpoints is known to the building agent. Depending on the system, the building agent can either use only the models for heating and cooling, or also the model for energy balance of the tank to estimate the expected behavior of the building.

In case of a pre-scheduled load shift request, the building agent will use the simulation model to compute whether the electricity consuming or producing HVAC components will actually be running at the time the load shift is requested. If this is the case, the fact that these models are simple enough to be reversible in time can be exploited to get the potential load shift action. Depending on the degrees of freedom the building agent is given, measures could be

- preheat the building,
- preheat the building and fill the storage tank, or

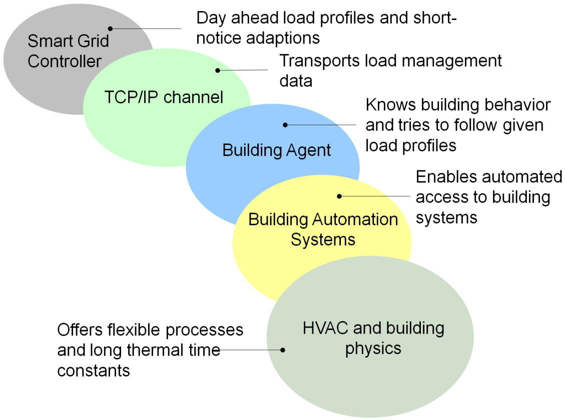

Fig. 2. Components in B2G communication

- preheat the building to a temperature above the usual setpoint, as in the example shown in Fig. 1, where the controller anticipates the early morning peak.

Similar actions are, if for instance CHP is used and heat has to be stored during the load shift,

- let the building cool down or
- let the building cool down and empty the storage tank as well.

All these measures can be scheduled properly by using equations 2, 3 and 6, to compute either directly the control signals for the HVAC system, or to compute new setpoints for the system which will lead to a schedule close to the one computed, while enabling the building agent to exploit the controls strategies actually implemented in the BAS. It should be duly noted that this design of the building agent offers many opportunities to augment the agent, e.g. by introducing machine learning into the agent, therefore enabling the agent to adjust the time constants or consumption values based on monitoring data gathered by the BAS.

IV. COMMUNICATION PROTOCOLS

The presented system is based on the concept shown in Fig. 2. In this structure, the main components are the smart grid controller (SGC) and the building agent (BA), connected by a TCP/IP channel. The SGC represents the smart grid, while the BA embodies the building. Communication between these two partners is essential. The communication module is discussed in this Section.

It is divided into two domains-the building domain and the smart grid domain. For each direction different communication requirements and hence different protocols must be considered.

The main purpose of the agent in the building domain is to manipulate the internal systems in a way that the desired load schedule is matched. For that reason the BA needs to interface with the BAS of the building it is in control. Beside proprietary solutions, automation of functional buildings is dominated by the open standards BACnet (Building Automation and Control Networks), LonWorks and ZigBee – all of them provide interfaces which can be used to tune the building systems accordingly [7][8].

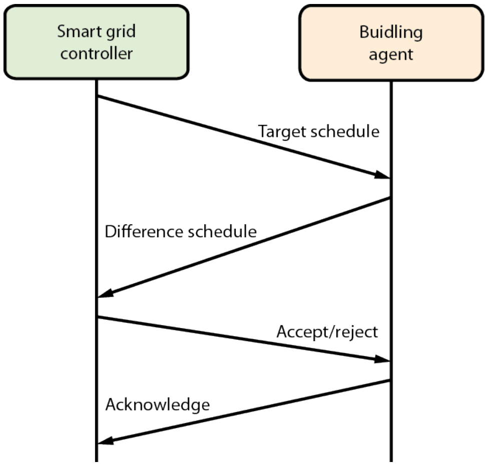

Fig. 3. Communication scheme

Contrary to communication in the area of building automation, the landscape in the smart grid domain is less definite. While the need for standards was recognized and standardization efforts are in process by a number of national and international institutions, there exist still several different possibilities for the path from building to the smart grid.

As initial step towards a suitable standard, the communication requirements between SGC and BA must be defined. Figure 3 shows the generic communication scheme, which is used between the controller and its connected agents. The grid controller has a defined load schedule for the next day, and must follow it as closely as possible by using the connected buildings. As a first step, the controller sends the defined schedule to each of the connected BAs. The agents in turn respond with a schedule that is optimized to fit the request of the controller and wait if it accepts or rejects the proposed plan. The controller then combines the received proposals in a way that its defined schedule is matched and responds accordingly.

An essential property of this approach is that the load schedule requested by the SGC is no load profile in absolute numbers that must be followed by the building. Instead it's the difference in energy, the controller needs its buildings to use in the defined timeslots. The agents respond accordingly with the amount of energy that is used less or more at each point in time. This distributed scheduling process can be terminated after one cycle or repeated to get improved results by using adapted target schedules.

In the last preceding paragraph the used communication scheme was discussed. The communication protocol used in B2G must support this scheme. As the load schedule represents the core of the data which must be communicated, it is the decisive criterion for the choice of communication protocol. In the following, possible protocols and standards

are analyzed in this light.
In perspective of grid management three standards, defined by the International Electrotechnical Commission (IEC), dominate the field. The IEC 61970 defines the Common Information Model (CIM), a generalized model, intended for standardized data exchange and interaction in the electric grid, while the IEC 61968 standard series extends the CIM by models for distribution systems [9]. It specifies among others, a data model for load control, as part of the interface for meter reading and control [10]. Beside these two norms, the IEC 61850 defines standardized communication in the area of substation automation. It was extended to cover different areas, like distributed resources (DR). The standard provides hierarchical data models, defined specifically for the domain in focus. In this paper, especially the scheduling model specified for the DR domain is of interest [11].
These three standards are mainly concerned with interoperation of different parties in the electric grid. However, there are two extensions of common building automation protocols that aim at demand response and load management specifically. The BACnet Load Control Object extends the BACnet protocol and provides basic means for initiating load shedding events [12]. A more sophisticated extension represents the ZigBee Smart Energy Profile (SEP) [13]. Beside demand response/load control capabilities, the SEP offers models for several other smart grid related tasks, like metering or pricing. Communication is based on a RESTful (REpresentational State Transfer) architecture, a simple web service relying on HTTP [14].
The open automated demand response (openADR) communication specification is a dedicated demand response standard. It defines a communication data model for predefined, price-based demand response programs. Beside transmission of price signals, event schedules are part of the specified models. Alike to the ZigBee SEP, communication in openADR is based on REST[15].

IEC 61968, IEC 61850, ZigBee SEP and openADR all offer the facilities to communicate load schedules, as required and can be used as base for the SGC to BA communication. In B2G openADR will be used for this purpose, as the BA is based on a custom software platform provided by a project partner, which supports openADR by default.

V. RESULTS AND CONCLUSION

In this paper, we seek adequate description models for the thermal behavior of functional buildings. The adequate modeling of demand response resources such as buildings is essential for effective scheduling algorithms that dispatch the demand response operations of multiple buildings. Too detailed modeling leads to large computation and communication overhead as well as complex scheduling, too simple modeling results in poor demand response operation (inadequate load profile adaption and/or restrictions in user comfort). The modeling approach described in this paper uses a piecewise model reduction to 1^{st} order thermal modeling as described in Section III.

TABLE I
EXAMPLE FOR COOLING TIMES (AIR EXCHANGE RATE IS 0.5 1/H, OUTSIDE TEMPERATURE -12 C, NO INNER THERMAL LOADS)

Building	**Year of construction**	**Specific annual heat energy demand [kWh/m^{2}a]**	**Time constant (cooling) [h]**	**Cooling Time from 22 to 20 C [h]**
Residential	1992	104	122	7.3
Residential	1994	75	124	7.5
Residential	1994	108	86	5.2
Residential	2003	35	128	7.7
Office	2009	20	206	12.4

For an experiment that shall demonstrate load shifting and its minimum impact on user comfort in a building, five different representative buildings in the Smart Grids Model Region Salzburg [16] have been selected and analyzed according to the methodology outlined in Section II and III. The buildings have different usage (residential, office, sports hall) and different age. Their specific annual heat energy demand varies from 20 and 200 kWh/(m^{2}a).

These results are shown in Table I and reveal that there are large flexibilities in the thermal system. The time constants are much longer than initially expected.

VI. OUTLOOK

This result is very encouraging for the next step: In a subsequent experiment and monitoring phase over one year, grid-optimized operation of the buildings will be tested. In this experiment, the technical, organizational and economic properties of demand response with functional buildings in a central European setting will be evaluated. The results of this experiment will find immediate application in a innovative building project in Salzburg. This special building complex will be designed in such a way that it offers on one side maximum comfort for the inhabitants, on the other side large shifting potentials in the HVAC system. The building will be supplied by multi-modal heating systems (solar thermal system, district heating, combined heat and power) and have a considerable heat storage capacity. It will be utilized as a showcase for the features of future smart grids. These features will not only focus on load shifting and renewable heating energy, but also energy feedback for users, electric mobility and future living concepts.

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