Determination of load schedules and load shifting potentials of a high number of electrical consumers using mass simulation

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ABSTRACT

The massive growth in the usage of renewable, but fluctuating energy sources in connection with the energy turnaround calls for a similar growth of the integration of flexible loads. This seems to be a vital aspect to maintain the balance between production and consumption in the transportation grid as well as in the distribution grid at low voltage level. In this regard the question of how to achieve a flexible and cost efficient mass integration of low power demand facilities like domestic heat pumps is of special interest.

The Center for Demand Side Integration at the University of Applied Sciences Hamburg and Energie Baden-Württemberg (EnBW, the 3rd largest utility in Germany) developed and tested control algorithms in a simulation project in order to integrate a large number of distributed consumers (several 10.000) into an integrated system. The behaviour of the system was analysed with regard to load prediction, scheduling and shifting potentials.

INTRODUCTION

The electrification of heat supply in residential buildings and therefore the connection of electricity and heat demand cannot only increase the efficiency regarding primary energy consumption, but also holds the possibility to integrate these consumers as “smart” applications into the electricity supply system. Electrical heating systems like heat pumps (HP) or night storage heaters (NSH) can have a big flexibility to postpone their electrical consumption. Due to installed storage systems and/or the storage capacity of the in-house heat distribution system the electricity demand can partly be decoupled from the heat demand. Heating systems in the residential sector, especially heat pumps, only have small installed loads but can be aggregated to switchable loads of a significant dimension. In order to enable an operator to take control of a swarm consisting of a large number of small consumers, special algorithms need to be developed which enable the aggregation of the flexibility in power consumption and the monitoring of the system. Also thermal marginal conditions have to be met to ensure that no loss of comfort arises due to too high or too low room temperature in the buildings or a lack of hot tap water.

SYSTEM DESIGN AND ELEMENTS

The objective in the development of the system design was to create a structure that enables efficient communication and a central control and monitoring of a system for Demand Side Integration, which consist of a large number of system elements (tens of thousands). An additional requirement was the day ahead scheduling of the consumers participating. In order to optimize the procurement of energy at a wholesale market, a day-ahead load schedule needs to be generated for all of the consumers. It had to be taken into account that a demand-dependant planning makes the knowledge of the demand behaviour and the state of all the systems elements mandatory. To collect and evaluate this data centrally would lead to an immense data volume. A further aspect is the scheduling problem itself. Often used methods like LP (Linear Programming) or MILP (Mixed Integer Linear Programming) can be used for the scheduling of single or comparably smaller groups of applications. The speed in finding the optimal solution and the computational effort depends on the constraints, the number of applications and the objective function. Especially the dispatching of a high number of applications with similar parameters leads to a flat solution tree which slows down the finding of the optimal solution dramatically [1]. A central approach for this scheduling problem would not be feasible regarding the computational overhead or at least limit the scalability of the system.

On the basis of these considerations an agent based concept was used where decentred control and scheduling are realized. This concept bears additional advantages regarding the reliability and extendibility of the system. During a failure of communication an autonomous agent can fall back on a load schedule that was generated earlier or an emergency schedule. New participants can easily be integrated without changing the central data stock.

Components of the system and system architecture

The top-level entity of the system is formed by the dispatcher. Analogous to power plant dispatching the dispatcher optimises the operation of the whole system, gives guidance for the generation of the day-ahead load schedule and is able to change the behaviour of the swarm within the day. Based on external information such as shortages in the distribution grid or current prices at the

stock exchange the dispatcher can take action and induce changes of the predetermined load. Together with the aggregator the dispatcher forms an entity. Here information about the participants is collected and evaluated for the dispatcher and information is distributed to the underlying level of subaggregators. The dispatcher only has crucial information about the system in an aggregated form.
The subaggregators communicate directly with the participants. They provide two basic services. First they aggregate information from the consumers and calculate key figures on the current state and the flexibility of the system. Second they distribute requests from the higher level to the participants. Each subaggregator stands in a 1:n-connection with the consumers.
Every participant is connected via a control box (CB). This device contains all necessary algorithms to predict the heat demand and to plan, monitor and control the operation of the heater. Throughout the day short term load changing as well as long term shifting potentials are determined.
The knowledge about the system's current state is more and more abstracted with a rising level in the system's structure. Besides the reduction of traffic by introducing levels of aggregation, encapsulation of consumer groups can be done to depict network topologies, making a local network congestion management viable. [2]

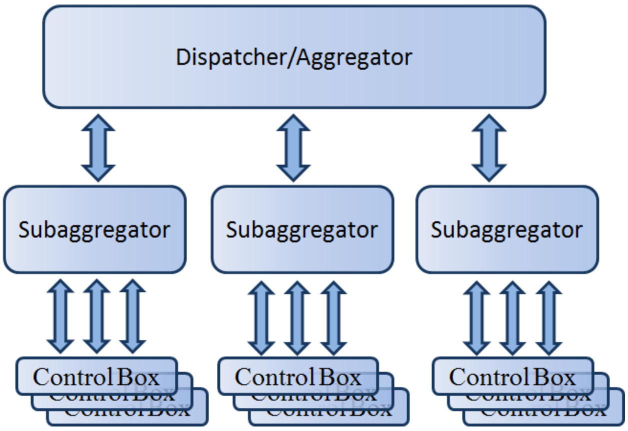

Figure 1: three level system architecture

Due to its modularity this communication structure offers a high degree of scalability, which is of large interest for a mass simulation as well as for a real system. Also the data security plays a major role in the system design. The described system ensures that no individual data needs to be stored outside the CB. Due to the fact that all individual data is aggregated before being passed to the top level information on individual households has to be stored nowhere but in the local CB.

Concept of operation

In this project an electricity-led operation mode was designed in which the planning and scheduling of the consumers is done on the basis of a building specific characteristic curve for the heat demand. A similar concept was developed in [3]. In a field trial it could be shown that the control of domestic heat pumps on basis of a characteristic curve for the heat demand can yield a control success comparable to a conventional heat pump regulation. This kind of control is not achieved on the basis of measured temperature levels in the return flow but the control of the heat pump is realised by a planning of the heat production itself. For every day the cumulative heat demand for the day is predicted whereafter the operation and heat production of the heat pump is planned in advance. Before a consumer can be switch to an electricity-led, predictable operation mode, the ambient temperature dependent heat demand as well as the flexibility in heat generation has to be learned in advance. The CB contains a self-learning algorithm which, in a first step, observes the heat demand of a building as well as the resulting operation of the heat supply unit (HP or NSH).

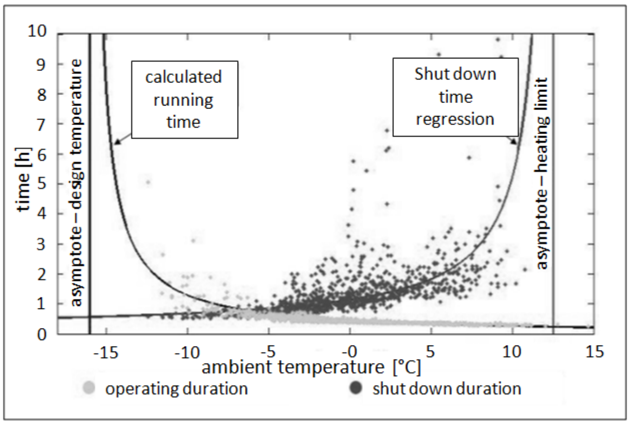

Figure 2: exemplary running and shut-down times of a heat pump plotted against mean ambient temperature

Key figures are evaluated describing the behaviour of the building regarding flexibility and heat demand. This knowledge is important to ensure a reliable planning and prediction of a HP or a NSH and to run an electricity-led control without affecting the comfort regarding availability of domestic hot water (DHW) or the room temperature. Figure 2 shows the running and shutdown times of a model of a domestic heat pump plotted against the daily average ambient temperature. This is crucial information to calculate the flexibility in shifting the electricity consumption. After a learning-phase the CB logs on to a subaggregator and is able to deliver a day-ahead load schedule and intraday the load shifting potential on the basis of the real thermal situation of the building (to be used for reserve capacity etc.).
The day-ahead scheduling is realized using a heuristic algorithm which uses the preliminarily learned parameters, a temperature forecast and a preference signal. The latter two are provided by the dispatcher. The preference signal indicates on an hourly basis which periods of time should primarily be used for consumption. Depending on the

technical parameters and a given preference signal not only one but a set of solutions would lead to an optimal load schedule for a single participant. By selectively adding random effects to the generation of a load schedule this flexibility was used to reduce the concomitances in order to smooth the total load schedule of the swarm. This non-deterministic heuristic algorithm can be run on a simple micro controller.
During the day deviations of the current load from the predefined load schedule are mitigated using a bidding based regulation.

REALIZATION OF THE SIMULATION TOOL

Stand-alone models of heat pumps, night storage heaters and the supplied buildings were built and validated using Matlab/Simulink. From there the models where exported as dynamic link libraries (.dll) into the JAVA based mass simulation Framework JADEX. A control and communication infrastructure was added likewise, consisting of control boxes in the buildings, sub-aggregators and a central aggregator and dispatcher. Using the JADEX framework, mass models of several 10.000 individualized buildings with their heating infrastructure were simulated in small time steps (one simulation step per minute of simulated time).

Building model in Matlab/Simulink

Using Matlab/Simulink, models of buildings containing heating systems and DHW tanks were designed in order to depict the thermal behaviour of the whole system consisting of heat generation, storage, heat distribution and heat demand in a dynamic simulation.
The reason a detailed simulation of single buildings was realised was on the one hand to take into consideration the temperature dependant heat demand as well as the usage dependant heat demand (due to e.g. ventilation or DHW usage). On the other hand only in a building wise simulation the effects of different building physics resulting in different heat capacities or a variation of storage and heat distribution systems can be taken into account.
Figure 3 shows the simplified structure of the model exemplified by a building with a brine/water HP and a floor heating system as well as radiators. For the simulation measured time series in time steps of one minute for ambient temperature and solar radiation were used.
In buildings which are equipped with heat pumps the hot water preparation is usually also done centrally with the HP. Houses with NSH however have decentral hot water preparation with electric flow heaters. The DHW storage tanks were modelled as stratified storage tanks [4]. Usage dependant withdrawal profiles were generated using the tool DHWcalc which was developed by the Technical University of Denmark in association with the university Kassel. It allows generating profiles for DHW-demand on a stochastic base [5].

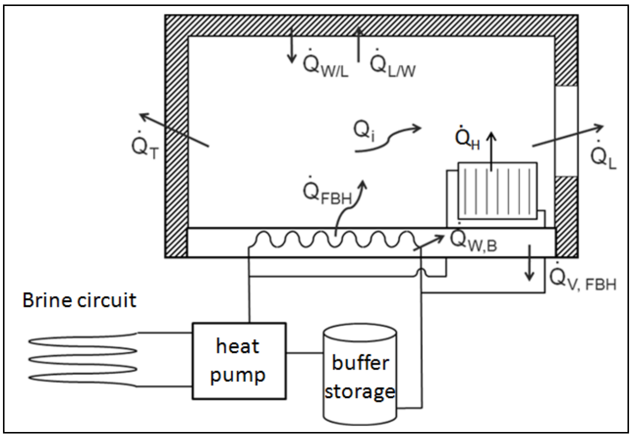

Figure 3: schematic model structure of building with B/W-heat pump

Mass simulation in Jadex

Jadex provides a multi-agent platform for both extensive conceptual possibilities and toolsets including analysis tools for the creation of complex distributed applications. It contains a programming framework and an execution middleware. [6]
The buildings agents are dependent of various (environmental) parameters which are provided by the framework. Furthermore they are in a reciprocal relationship with the Matlab DLLs that encapsulate both the thermal models and the CB. Dynamic Link Libraries (DLLs) are generated from the previously described Matlab models. Any parameterization as well as the internal data storage of the models is removed and interfaced to the outside. The resulting DLLs are stateless and are used as so-called re-entrant DLLs. This results in two advantages:

- Not every building agent requires a separate DLL, which dramatically reduces the storage overhead.
- Support on Windows. Windows allows a Java process to only hold 117 different DLLs simultaneously.

Results of the simulation

The objective of the simulation approach was on the one hand to develop and test the algorithms. On the other hand the behavior of large swarms of consumers was analyzed regarding the reliability of load schedules and load-shifting as well as scale effects.
Two different types of load schedules can be generated using the developed simulation tool. First load schedules can be generated using the preference signal provided by the dispatcher. The other alternative aims at generating a stable load. In this case the running times of the consumers alternate, resulting in a load schedule with the smallest concurrency possible.

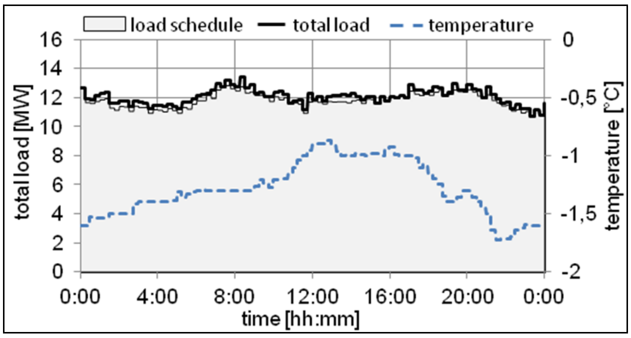

Figure 4: stable load planned for a winter's day for 10.000 HP

Figure 4 shows an example of a day during winter with a stable planned load for 10.000 heat pumps. The total load is plotted as the quarter hourly average.

The unstable heat demand due to a high hot water demand in the morning and the evening results in two bumps at around 8 a.m. and 8 p.m.

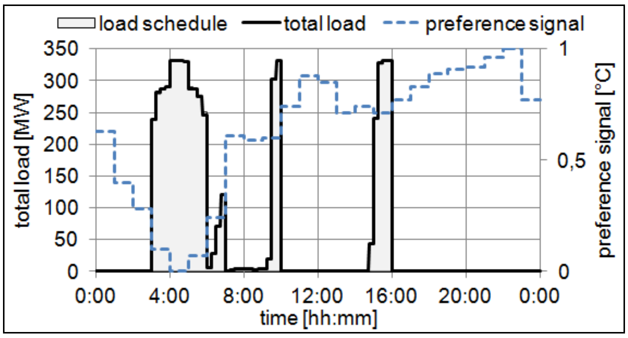

Figure 5: winter's day load schedule for 10.000 NSH using a preference signal

Figure 5 shows the planned and the real total load of a swarm consisting of 10.000 NSH. The load is planned using a preference signal which is also plotted in the figure. On this day the predefined load schedule could be met perfectly.

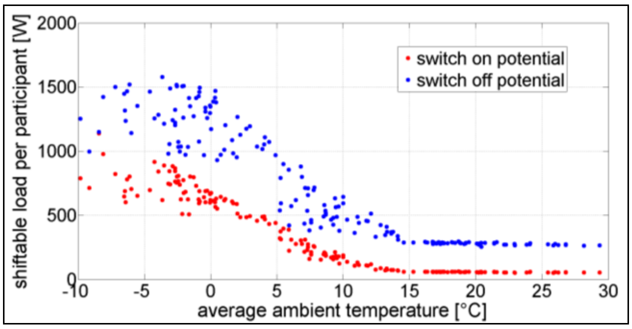

Figure 6: average intra-day load shifting potential for one hour per HP

Figure 6 and 7 show the potential for load shifting during the day for a period of time of one hour. The negative as well as the positive potential have a strong temperature dependency. When comparing HP and NSH the latter one shows a much higher flexibility in relocating their consumption. Also NSH have a large installed load in relation to the heat demand of the building because they directly convert electricity to heat, and they usually are dimensioned to cover a day's heat demand in a maximum time span of about 8 hours.

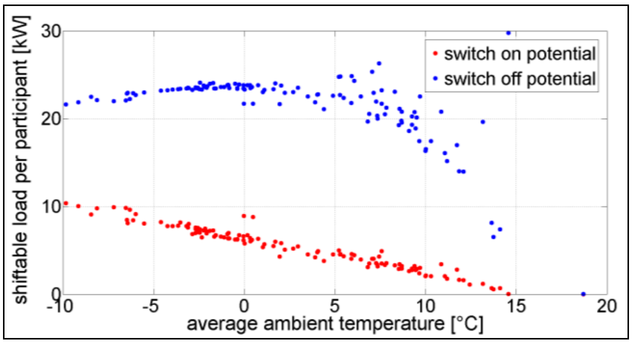

Figure 7: average intra-day load shifting potential for one hour per NSH

Conclusion

This article presents the design of a system for demand side integration of heating applications, which allows a day-ahead scheduling of the participants as well as an intraday re-dispatch. The conducted mass simulation implies that such a system would have strong potentials and reliability for the DSI loads pooled in it. The described modularity of the architecture and the methods for scheduling allow for a high degree of scalability.

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