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Evaluation of Business Models for the Economic Exploitation of Flexible Thermal Loads

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Abstract—This paper describes a software tool for simulating the economic exploitation of flexible thermal loads, in particular by providing tertiary frequency control reserves and by intra-day trading. The tool consists of several components, comprising the simulation of the dynamics and the pooling of small load devices, the reserve capacity auctioning and delivery request mechanism of the transmission system operator, and the optimisation-based dispatch of control signals to the individual devices. The results of a time simulation of 5,000 heat-pump water heaters for large buildings (e.g. multi-family residences) are presented. Tertiary control provision leads to a yearly gross benefit of about EUR 100 per water heater, whereas for a combination of tertiary control with intra-day transactions, a yearly gross benefit of more than EUR 1,000 per water heater is expected.

Keywords—smart grid, intra-day, ancillary services, demand response, simulator, business model

I. INTRODUCTION

The integration of large quantities of renewable energy in the context of the so-called energy transition (“Energiewende”) in Switzerland [1], [2], Germany [3], and other countries [4] is an ambitious goal. In order to operate an electric power system with large shares of wind and solar energy, additional operational flexibility is needed [5]. The spatial and temporal discrepancy between supply and demand requires the expansion of grid infrastructure and additional energy storage capacity.

A relatively new way to increase the operational flexibility of the power system is the coordination and joint optimisation of thermal loads, which possess an inherent “slack” [6] in their power consumption, in order to actively shape the power consumption profile of a large group of units. These approaches are usually referred to as “Demand Response” methods [7] and have become a major field of power system research in the last few years. Unlike the traditional peak shaving approaches such as [8], [9], which serve to decrease the maximum load, or control methods that try to avoid the so-called Cold-Load Pickup (CLPU) [10], [11] of thermal loads, many recent Demand Response approaches are targeted at controlled decreases and increases of the load in order to supply system services such as frequency control. A large portion of publications in this field is aimed at reliable setpoint tracking of a large population of units, e.g. [12], [13], [14]. In these approaches, the groups of pooled units have to be quite large (on the order of several thousands) in order to achieve a semi-continuous shaping of the power consumption curve.

The economic implications of reserve provision by load units have been investigated by, e.g. [15], [16], [17]. However, these research efforts have been targeted at specific use cases of load flexibility and usually only take into account a single market for the economic exploitation.

This paper describes the components of a generic simulation environment for the calculation of the economic potential of various “SmartGrid” applications. The simulator is able to quantify annual gross revenues which can be achieved by taking advantage of the flexibility of loads. The methodology is based on pooling (aggregating) flexible loads and on the application of a multi-stage stochastic optimisation model. In this process, optimal bids for various market segments are created. A market model is implemented which represents the entire bidding and delivery request process for reserve power provision in a realistic way. We will focus on the Swiss ancillary service market [18] in order to base our simulations on a concrete and realistic setup. However, the simulator can be adapted quite easily to other market environments if necessary. According to the acceptance or rejection of the placed bids, schedules and request scenarios for the pooled flexible loads are created.

The base case takes advantage of the operational flexibility of the hot water storage tanks of heat-pump water heating systems for providing tertiary control reserves in Switzerland. By using historical price data, historical reserve request data, and parameter sets of real buildings, the costs and revenues for an exemplary year are calculated.

The present paper is largely based on [19]. It is structured as follows: Section II describes the version of the simulator which is tailored to the base case. Section III describes the individual components of the base case, as well as the objective function of the stochastic optimisation. Section IV presents the results of the base case and a simulation for individual days with tertiary control power provision in combination with intra-day transactions. Apart from the examples presented in this paper, further scenarios can be simulated. Part V provides an outlook on future work. Special attention is given to the question if economically viable business cases can be exploited already today, and if not, which additional requirements would have to be fulfilled.
II. DESCRIPTION OF THE BASE CASE

A. The simulator

Figure 1 displays an overview diagram of the simulator. The simulator consists of modules that are largely independent of each other. The core of the individual modules is formed by mathematical optimisations with various objective functions and constraints. The results of a module are transferred to the next module as inputs. The arrows in Figure 1 show this flow of information between the modules.

The trading department generates tertiary control power (TCP) bids, which are either accepted or rejected in the TCP auction of the Transmission System Operator (TSO). As a consequence of this, tertiary control energy (TCE) prices are tendered and the schedule optimised. In the event of a delivery request, the schedule is adapted according to the amount of power requested. By means of a process optimisation, the schedule is distributed among the thermal loads.

B. The thermal loads model

A pool of 5,000 water heaters is used for the base case. The water heaters are heated via heat pumps that have an electrical input of 17 kW each. Their capacity of 3,000 litres is a typical size for an apartment building.

A separate model was developed in order to represent the behaviour of the thermal loads in the simulator. Figure 2 shows that the simulated values are consistent with the measured values and the model closely reflects the real situation. The number of load cycles, the duration of the load cycles and the initial and final temperatures are closely matched. In the real system, the circulation pump is switched off between midnight and 04:00. This keeps the upper temperature of the water heater more or less constant. Once the circulation pump is switched on, the upper temperature falls rapidly. In this respect, switching off the circulation pump can be neglected.

Fig. 1. Concept of the simulation with the modules for an optimum bidding strategy, auction, schedule optimisation and process optimisation

With the specified temperature range of between 45°C and 65°C, approximately 1/3 of the thermal storage capacity can be exploited for economic gain. In the present case, hardly any temperature stratification is present due to the circulation pump. In the general case with stratification, higher flexibility can be assumed.

C. The tertiary control market in Switzerland

The base case considers the tertiary control market in Switzerland. Swissgrid is the TSO in Switzerland and the sole consumer of control power, i.e. it has a monopoly on demand. Payment is made via a pay-as-bid auction. Swissgrid announces its demand for control power prior to the auction. This demand is price inelastic and generally constant.

In Switzerland, tertiary control power is traded based on 4-hour blocks and weekly bands. Only 4-hour blocks are considered in the base case. They are numbered according to the time of day (block 1 = 00:00 – 04:00, block 2 = 04:00 – 08:00, etc.). One block has a minimum size of 5 MW and can be enlarged by increments of 1 MW.

There are separate bids for the provision of control power (TCP) and the supply of control energy (TCE). The TCE bid can still be adjusted afterwards. In the event of a delivery request, the TSO selects the bids with the most favourable TCE prices, i.e. the supplier can influence the probability of a delivery request via the bid price for TCE.

The structure of the bids is based on a TCP price forecast. Figure 3 shows an extract of the price forecast with subsequent price optimisation. The grey area represents the historical price range of the accepted bids. The TCP price forecast is indicated by the blue line. The forecast prices were scaled with an optimisation and are illustrated by the red line. From this, one can identify that the price forecast is generally at the upper limit in the grey area and therefore provides realistic prices that are close to the clearing price.
At the end of August, the TCP prices suddenly increased sharply for the negative block between 00:00 and 04:00. Subsequently, the deviation in the forecast was greater than normal for several days. If the forecast turns out constantly to be too high or too low over an extended period, this is corrected with the price optimisation.

III. SIMULATION COMPONENTS

A. Optimum bidding strategy (module 1)

The optimum bidding strategy is crucial when it comes to assessing a business model. The mathematical formulation is complex and extensive. The optimisation considers both actual costs for energy and balancing energy as well as notional penalties, such as the temperature deviations of thermal storage units from their target value. Penalties are any costs that arise if a soft constraint is infringed. These notional costs must be determined in relation to the actual costs that are incurred, which requires a certain amount of experience.

Whether a block is called for delivery or not is not known at the time the bids are structured. The TCP delivery request method is not predictable. This is due to the nature of the subject, as it is the purpose of control power to balance out unforeseen events. Nevertheless, the individual probability that power will be called off can be influenced by the price bid for control energy (TCE).

In the stochastic optimisation, the opportunity costs for the provision and the costs in the event of a delivery request must be weighted according to their probability. It is for this reason that a series of scenarios is calculated for the optimisation. In each scenario, a particular combination of blocks is called, generating opportunity costs for TCE and future balancing energy. Each of these scenarios is weighted with a probability in the objective function.

The scenario without delivery requests is the most likely, as this is the one that is most common according to historical data. In the optimisation, the other scenarios are assigned the same probability of a request occurring.

A delivery period is assumed to cover a full 4 hours. However, the delivery period is implemented in the simulator in such a way that shorter deliveries can also be included in the scenarios.

The most important decision variables in the optimisation are the size of the blocks and the schedule. The schedule is optimised once more following the TCP auction (module 3). Once the TCP auction has been conducted, the accepted blocks form hard constraints for the following modules.

The objective function of the mathematical optimisation problem is as follows:

$$
\min C_{\text{tot}} = C_E + \sum_{s \in S} (C_{B_s} \cdot w_s) + \sum_{s \in S} (C_{U_s} \cdot w_s)
+ \sum_{s \in S} (C_{\text{pen}_s} \cdot w_s) - \sum_{s \in S} (G_{E_s} \cdot w_s)
- G_{\text{Ld}} - G_{\text{Lb}}
$$

(1)

where $w_s$ is the probability of scenario $s$ occurring, $C_{\text{tot}}$ are the total costs, $C_E$ are the costs for the day-ahead energy purchase (equal for all scenarios), $C_{B_s}$ are the costs for schedule deviations (balancing energy) in each scenario, $C_{U_s}$ are the costs for soft constraints concerning the state of charge of the water heaters, $C_{\text{pen}_s}$ are the penalty-costs for non-compliance during TCP-calls, $G_{E_s}$ are the revenues for delivered TCE and $G_{R_s^{\text{pos/neg}}}$ are the revenues for provision of positive/negative TCP.

B. Auction process (module 2)

The TSO assesses the bids and accepts those with the most favourable prices. As part of this process, the TSO carries out an optimisation that minimises its total cost for the required control power. This can result in bids being rejected even though the price is below the clearing price (see Figure 4).

Separate daily auctions take place for each 4-hour block as well as for positive and negative tertiary control power. These auctions generally occur two days before the supply date. In addition to this, an auction takes place each week for positive and negative weekly bands.
Equation (2) shows the mathematical formula of the objective function for this optimisation problem:

$$\min \ C = \sum_{i \in G} \sum_{j \in S_i} L_{i,j} \cdot p_{i,j}^L \cdot z_{i,j}$$ (2)

where $C$ are the total costs for the TSO (Swissgrid), $L_{i,j}$ are the volume bids, $p_{i,j}^L$ are the price bids and $z_{i,j}$ are the decision variables (accepted / not accepted). $G$ is the set of all bids, consisting of a set of multi-level bids $S_i$. A multi-level bid is a conditional bid consisting of multiple volume/price combinations, from which a maximum of one can be accepted.

C. Schedule optimisation (module 3)

As the provision of control power has an influence on the organisation of the schedule, and vice versa, the TCP and schedule optimisation processes are closely linked to one another. The formula for schedule optimisation is similar to the one for TCP optimisation. The main difference is the fact that the amount of control power to be kept available for the schedule optimisation is already known. It represents a hard constraint.

The most important aspects for the schedule optimisation are the minimisation of the costs for the energy and the provision of sufficient power and energy reserves. Which TCP blocks are requested and how long a delivery lasts is still unknown. Whereas the TCP optimisation scenarios were defined with a maximum of one delivery request, a complete scenario tree is generated for the schedule optimisation. Each accepted TCP block yields the variants "delivery request" and "no delivery request". If, for instance, both a positive and a negative block are accepted for a 4-hour period, 3 possible delivery scenarios arise with their corresponding probabilities, namely positive delivery, negative delivery or no delivery request. If, for example, on one day, positive and negative bids are submitted for all 6 blocks, $3^6 = 729$ scenarios are produced. The calculation of the probabilities is based on a statistical analysis of historical delivery requests.

The historical data shows, for example, that the probability of a delivery request occurring for block 2 (04:00 – 08:00) is greater when a delivery has already been made for block 1 (00:00 – 04:00). In order to simplify the calculations, however, it was assumed that the probabilities of the events were independent of each other.

The TCE price can be used to influence the probability of a delivery request. Correspondingly, the costs/revenues of a delivery are also dependent on the request probability and on the TCE price. For the schedule optimisation, the TCE prices were set to zero and the request probabilities were fixed in accordance with the historical data. Whether a delivery takes place or not is predetermined by the delivery request scenario. The TCE price therefore has no influence on the schedule optimisation. The advantage of this method is that the costs of the various scenarios can be compared with and without delivery requests when the TCE prices are subsequently calculated.

The mathematical formula for schedule optimisation is therefore as follows:

$$\min \ C_{tot} = C_E + \left( \sum_{s \in S} C_{Bs} + \sum_{s \in S} C_{qs} \right) \cdot w_s (3)$$

The identifiers correspond to those in (1).

D. Simulation of a delivery request for control energy (module 4)

The decision on which bids are requested for delivery in the event of a demand for TCP is taken in a similar manner to the TCP auction (see section $B$). The demand is covered by a minimum-cost combination. The power that has been offered is delivered either in full or not at all. That is why the block size also plays a role in addition to the TCE price.

Figure 5 presents the histogram of the delivery requests for tertiary control power for the period between 01/01/2010 and 31/05/2012. No power was requested for 70 percent of all the fifteen-minute periods. When a request does take place, this is generally in the region of +/- 50 to +/- 150 MW.

Figure 6. Notional clearing price curve for the delivery request of control energy.
The TCE prices are not published in Switzerland. The amount of control power that is requested and the prices for balancing energy are however published by the TSO. This information enables a clearing price to be determined for each quarter of an hour and a notional clearing price curve to be generated for the simulation (Figure 3).

E. Process optimisation (module 5)

Process optimisation controls the individual loads. On the one hand, the schedule should be adhered to as far as possible, yet, on the other hand, the storage capacity of each individual load should be kept within the permissible limits. On a day without provision of control power, the schedule is only disrupted as a result of unforeseen load variations.

Penalties are specified in the case of schedule deviations and in the event that the temperature limits of thermal storage units are infringed. The penalties enable both of these conditions to be given different weightings. During a delivery, the weighting for adhering to the schedule is increased to avoid penalties in the event that a delivery request is not complied with.

The probability of a scenario with at least one delivery request occurring may be higher than the probability of no request taking place. It is therefore possible that too little or too much energy was purchased when using the schedule optimisation. This can mean that the schedule has to be adjusted in intraday trading if a delivery does not take place.

A model predictive controller (MPC) was implemented for the process optimisation. At each decision-making stage, a time frame in the future is considered and from that, the optimum decision for the current time period is calculated.

It must be ensured that the delivery request is unexpected from the controller’s perspective. This is a prerequisite for a realistic simulation. As in reality, there is no way of the controller obtaining a better starting position prior to the request.

The mathematical formula of the objective function for process optimisation is as follows:

$$\min \ C = \sum_{t=1}^{N_H} C_{q_t} + \sum_{t=1}^{N_H} C_{p_t}$$

(4)

where $C_{q_t}$ are the costs for the soft constraints concerning the state of charge and $C_{p_t}$ are the costs for deviations of the power setpoint. Both terms are piecewise linear functions with variable penalty costs depending on whether TCE is called or not.

IV. RESULTS

A. Results of the base case

In the base case, revenues of around CHF 510,000, i.e. CHF 100 per water heater and year, were generated for 2011. The prices for TCP were low in 2011. As a consequence of this, the profits from the provision of TCP were equally modest.

Due to high TCP prices, February 2012 generated revenues of over CHF 250,000, i.e. 50% of the annual revenue of 2011. It should be noted at this point that, if space heating is also included in the model during this period, this will result in lower revenue figures. This is because heat pumps were heavily utilised due to the cold and flexibility was reduced accordingly. As, however, peak prices of up to CHF 2,299 per MW were paid for positive control power, February 2012 would still generate higher TCP revenues than other months.

The examples demonstrate the highly dynamic nature of such a system. Extreme market conditions can be exploited in an optimum manner. This has means that, despite high electricity prices, too much energy is occasionally purchased in day-ahead trading in order to re-supply it as control energy at an even higher price in the event of a positive TCP delivery and to make money out of the provision of TCP.

B. Influence on the TCP market

The TSO also profits from the procurement of control power as a result of the additional suppliers. In this respect, the costs for Swissgrid fall by approximately CHF 140,000 for the year under consideration, 2011. The cost reduction amounts to around 0.4% in relation to the total costs of around CHF 35 million for the provision of TCP. As the forecast prices are close to the actual clearing prices, there is little effect on the clearing prices. The influence of the heat pool as an additional supplier is small on account of its small size.

C. Incorporation of intraday trading

No intraday transactions are considered in the base case. Intraday trading represents great additional potential for exploiting flexible loads. Compared against the minimum block sizes of 5 MW over a period of 4 hours, intraday trading allows much smaller amounts to be traded over a period of 15 minutes or one hour. In addition, very high spreads occur in Germany within one hour in intraday trading.

A component for intraday trading was added to the simulator and simulations for individual days were performed. The results are presented in Figure 8. The results suggest that the potential, when intraday is included, will increase by a factor of around 10.

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Fig. 7. The submitted and accepted blocks in July 2011. The transparent blocks indicate bids that were not accepted.
V. OUTLOOK

In the examples shown, the flexibility of domestic water heaters for multi-family buildings is exploited to generate maximum revenues on the control energy and intraday market. At the same time, the costs for procuring the energy on the spot market are minimised. In addition to the currently implemented feature, a further stage could consist of grid usage fees, synergies with other commodities such as natural gas and the trading of CO₂ certificates being modelled in the simulator.

In addition to heat pumps combined with water and space heating systems, other flexible loads lend themselves to this purpose, such as swimming pools, ice rinks, cold stores, direct electric heating systems, electric boilers, electric vehicles, washing machines, tumble dryers, refrigerators and many more.

Large loads such as cold stores or ice rinks appear to be of interest here because the necessary monitoring and control infrastructure only has to be installed once and the investment costs are kept within reasonable limits. Large loads are however often only slightly oversized. Efforts to increase energy efficiency also involve systems and electrical appliances (such as refrigerators) being designed for continuous load. Without increasing the size of such loads, exploiting their storage capacity is only possible to a very limited extent.

It is all the more important to examine which loads are of interest in terms of load management. The potential differs depending on the type of system and design. The knowledge that oversizing loads is detrimental in terms of energy usage but may provide interesting financial benefits in the longer term is influencing the design process of new systems. This potential can be optimally evaluated using a tool such as the one applied for this paper.

Ultimately, the simulator is used to identify interesting business models and quantify their economic potential. Thanks to the generic approach, sensitivities concerning changes to relevant market factors and political environments can be calculated. This in turn provides valuable information with respect to demands for an up-to-date market design, which takes the present production profile with its high proportion of new renewable energy sources into account.

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