FLEXIBLE THERMAL LOAD MANAGEMENT FOR ANCILLARY SERVICES MARKET: EXPERIENCE OF SWISS SMART GRID PILOT PROJECT

Elvira KAEGI
BKW FMB Energie AG – Switzerland
elvira.kaegi@bkw-fmb.ch

Daniel BERNER
BKW FMB Energie AG – Switzerland
daniel.berner@bkw-fmb.ch

Adrian PETER
BKW FMB Energie AG – Switzerland
adrian.peter@bkw-fmb.ch

ABSTRACT

This paper presents the successful introduction of a demand response product using domestic thermal appliances in the frame of a Smart Grid Pilot-Project of a Regional Power Supply Company in Canton Bern, Switzerland. This product is part of a home energy management tool using customized IP-based communication and a smart metering data management system. In this paper, direct load control algorithms are presented which flexibly control thermal devices while strictly complying with customer comfort requirements. We demonstrate how the Distribution Company can use domestic loads to offer balancing power for tertiary reserve, contributing to the smart grid business case.

INTRODUCTION

The new “FLEX” product for smart control of domestic thermal appliances was introduced and is being tested in the frame of the Swiss Smart Grid Pilot-Project iSMART. This project has started in Q2-2009 and is planned for the time horizon of Q3-2012. It involves several hundred residential customers in the BKW supply area (power supply company of cantons Bern and Jura, Switzerland).

The FLEX product involves flexible control of water heaters and heat pumps. Among 300’000 registered customers in the BKW supply area, water heaters alone represent a potential of 400 MW of installed power which can be used as system tertiary reserve. These appliances are currently controlled through fixed time-frame ripple control group switching, allowing for sufficient time to cover customer comfort requirements. One of the scopes of the iSMART Project is therefore to address the potential of flexible thermal load control using smart grid infrastructure, and to evaluate the related business case. During 2011, BKW plans to test the FLEX product (on a voluntary basis) with 50 domestic customers equipped with the smart grid infrastructure. In the following sections, we explain the principles of thermal demand response and describe the existing control methods. Further, we outline the smart grid infrastructure used for flexible load control and present the developed control algorithms, while explaining the rules of Swiss tertiary reserve market operation.

In the last section, the implementation details are given. The first field tests will be conducted during Q3 and Q4, 2011.

THERMAL DEMAND RESPONSE

Power system operation is based on instantaneous balance between generation and load in order to maintain the system frequency within its nominal settings. The day-ahead generation planning involves exact load forecast. However, the system power balance may be altered due to stochastic variations in load shape as well as power generation outages (fig. 1). Large frequency deviations may result in a system collapse if the system frequency exceeds the 50Hz ± 5% limits.

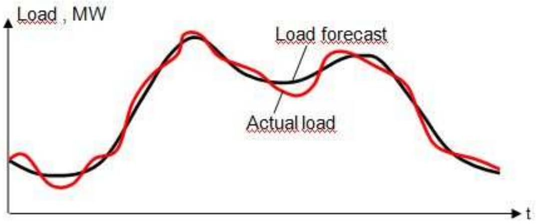

Fig. 1. Daily load deviations from forecast

Frequency deviations are corrected in three steps. Wide area primary control is triggered automatically (AGC, Automatic Generation Control) to stop the frequency collapse (fig. 2, shape 1) and to stabilize frequency deviation at Δf_{dyn}. Secondary reserve on a local basis is activated within 15 min and allows to reduce the frequency deviation to Δf_s (fig. 2, shape 2). Finally, the tertiary control is manually activated within 15 min to 1 hour and is aimed to restore the power balance at the nominal system frequency (fig. 2, shape 1).

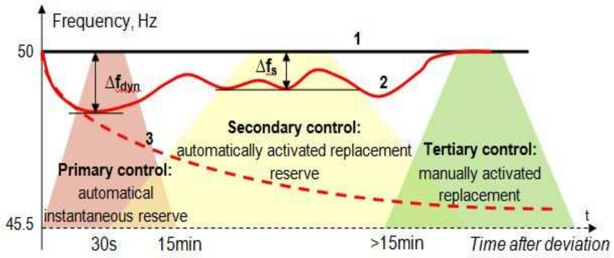

Fig. 2. Primary, secondary and tertiary frequency control

Tertiary control can be performed as well through generation reserve activation as through demand response mechanisms. Depending on the system need, demand response may also be used to increase demand at times of high generation and low demand, using smart grid communication infrastructure and optimizing available storage.

In this context, thermal appliances are well suited for demand response provision as they usually provide sufficient thermal inertia to sustain supply interruptions in a frame of tertiary reserve (time frame of 30 min to 4 h) without causing a discomfort for the appliance owner.

Physical Hot Water Storage Model

As described in [1], the relative thermal energy for heating / cooling devices using internal thermostat switching is given by:

$$E_{th,heat}^{rel} = \frac{T - T_{min}}{T_{max} - T_{min}} \quad (1)$$

$$E_{th,cool}^{rel} = \frac{T_{max} - T}{T_{max} - T_{min}} \quad (2)$$

Where T is the measured internal temperature [°C] normalized to an interval [0 1], T_{max} and T_{min} are switching boundaries of the device (hysteresis).

However, the physical model outlined in [1] is based on the assumption that online temperature measurements are available. Also, it was supposed that the appliance is able to bypass the internal thermostat which implies a change in existing internal appliance controlling. Taking into account the real field conditions of the present pilot-project, both above conditions are not actually satisfied. The control algorithms were therefore based on estimation instead of measurements of thermal energy stored in an appliance.

In the following sections, the existing thermal appliances management is described, followed by novel algorithms allowing for a flexible control in the frame of Swiss tertiary reserve market operation.

Existing Thermal Appliances Management

As mentioned before, the actual thermal load remote control is based on a fixed time-frame ripple control group switching.

Water heaters are controlled by daily ON-switching of control relays during 3 to 4 hours of the low tariff interval (usually 0:00 a.m. till 4:00 a.m.), depending on the water heaters group type. This timeframe is designed to be sufficient for any boiler in the group to fully heat up the water storage from ambient to operational temperature level. If the measured water temperature in the tank is lower than the operation threshold, the bimetal thermostat switches on and the water is heated until it reaches the upper operation limit temperature, upon which the bimetal contacts disconnect.

SMART GRID APPROACH TO THERMAL APPLIANCES MANAGEMENT

The new business case is based on the transferring of the appliances from the current demand management system to the smart grid infrastructure. Two-way communication channels with the national grid operator (Swissgrid) could be used to bid into the national ancillary service market as a Pool-ASP (Ancillary Service Provider). Benefits from those transactions would be shared with the actual owners of appliances.

Control algorithms developed for each type of thermal appliances are concerned with analytical methods for a real-time estimation of tertiary reserve potential, taking into account the specific operational framework of each type of appliance and Swiss ancillary service market operation requirements.

Further, some details of the Swiss tertiary reserve market operation are presented, followed by the outline of control algorithms used for boiler and heat pump control.

Participation in Swiss Tertiary Reserve Market

In order to participate in the Swiss Tertiary Reserve Market, prequalified ASPs should bid into a 2-days-ahead auction for 6 daily tertiary power blocks (6 x 4h). The ASPs that win the auction are then allowed to participate in the tertiary energy reserve auction, which takes place on both day-ahead and intraday basis. Tertiary power could be called only during the time intervals specified through the auction clearing at merit-order-basis (the less expensive offers are called first). ASPs are paid according to their bidding price and the actually delivered tertiary reserve energy (both for the withholding and for the actual balancing energy delivery).

Water Heater Load Control Principle

According to the reserve market rules specified above, the ASP may use two bidding strategies: 1) maximize its tertiary reserves during several daily bidding blocks using published price history; 2) maximize its reserve potential for every bidding block.

In the following section, we show how the balancing energy potential can be estimated.

In the practical case, the only measured state variable is the electrical power drawn by the appliance. As the water tank temperature is not known, the estimation is based on the assumption of a dependency between the heating / cooling period duration and the temperature being nearly linear, thus being identified by its slope coefficient k. Taking into account typical hysteresis parameters (T_{ON}=55°C, T_{OFF}=60°C) and defining the comfort limit temperature as T_{min}=45°C, it is possible to derive average cooling slopes of an appliance. For example, a typical average daily cooling slope coefficient of a 300 l, 6 kW water heater is k_{cool}=-0.4°C/h, while an average daily heating slope coefficient of such a water heater is approximately k_{heat}=15°C/h.

Using the above considerations, it is possible to derive the needed duration of the heating cycle Δt_{heat} from the required time interval when the temperature in the tank would reach the specified threshold temperature. The temperature difference between the initial state of this interval and the final state (T=T_{max}) would determine the duration of the next heating cycle. In order to assure both the maximal reserve power and the user comfort, the lower temperature operation threshold should be set to the minimum comfort temperature T_{min}. Using this estimation method, partial heating of the water tank would result in a potential load shifting to a earlier time slot, while a longer cooling period would lead to the potential shifting of the load to a later time slot (see fig. 3).

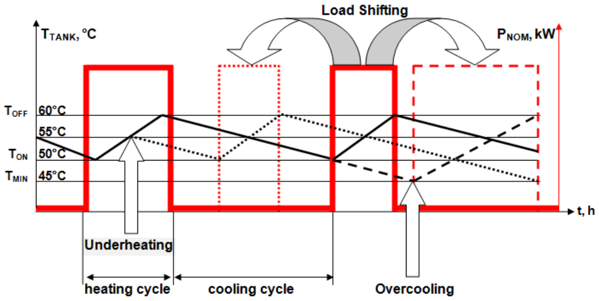

Fig. 3. Principle of water heater control

It is therefore possible to influence both the duration and the start of the heating cycle, thus being able to flexibly shift the electrical load of the thermal appliance. The tertiary reserve potential of each appliance for a given planning period can thus be derived (here, daily duty cycle of 96 discrete 15 min intervals).

The control algorithm based on the described thermal state estimation is presented below.

WATER HEATER LOAD CONTROL ALGORITHM

The Water Heater Load Control Algorithm is based on the above described water heater control principle.

Step 1. Balancing Energy planning over the period of 96 (15 min) intervals starts at 00:00 with the usual appliances commutation plan (ACP) update. The temperature estimation is set to the value of the last interval of the day before.

Step 2. Taking into account that water heater load is constant during operation, Balancing Energy Potential is defined as an energy E_B available for delivery or consumption during the interval Δt_B [h] between the start of the balancing energy request and the moment when the temperature reaches its critical limit leading to thermostat-governed state change:

$$E_B = P_{NOM} \cdot \Delta t_B,\ B \in n \tag{6}$$

$$\Delta t_B = \begin{cases} t_{Tmax} - t_n, for\ heating\ cycle \\ t_{Tmin} - t_n, for\ cooling\ cycle \end{cases} \tag{7}$$

$$T_{max/min} = T_n \cdot (1 + k) \tag{8}$$

where

P_{nom} is the rated power of the water heater, [kW];

Δt_B is the maximal possible duration of the balancing energy interval, for discrete intervals n=1:96;

T_{OFF} and T_{ON} are respectively maximal and minimal temperature settings of the water heater internal thermostat;

k is the cooling/heating slope of an appliance [°C/h], typically k_{heat}=16°C/h, k_{cool} = -0.33 to -12°C/h depending on the customer hot water consumption profile.

Depending on the duty cycle of appliance, the balancing energy potential is calculated for balancing energy delivery

$$E_{B-} = -P_{NOM} \cdot \Delta t_B \tag{9}$$

or consumption

$$E_{B+} = P_{NOM} \cdot \Delta t_B. \tag{10}$$

Conditions for balancing energy delivery for the time interval n:

1) Initial state of the relais at the time interval n:ON;
2) $T_{minON} \leq T_n \leq T_{OFF}$,

where T_{minON} is the estimated tank temperature after the period of minimal water heater Time ON. This time is necessary to preheat the water tank to the temperature which guarantees the agreed minimum comfort level (estimated empirically based on the individual hot water use profile). The maximal balancing energy delivery potential E_{B-} occurs for the condition:

$$\Delta t_B = \max\left(t_n - t_{Tmin}\right) \tag{11}$$

Condition for balancing energy consumption for the time interval n:

1) Initial state of the relais at the time interval n: OFF;
2) $T_{min} \leq T_n \leq T_{ON}$.

The maximal balancing energy consumption potential E_{B+} occurs for the condition:

$$\Delta t_B = \max\left(t_{Tmax} - t_n\right) \tag{12}$$

Step 3. Maximize potential profits according to available E_{B-}, E_{B+} and other optimization criteria (balancing energy market-price prediction, uncertainties in hot water usage profile, etc.) and bid into the balancing energy market according to tertiary reserve market rules.

Step 4. For confirmed bidding periods Δt_B, compute an Appliance Ranking List (as a merit order list based on nominal power and estimated E_{B-} and E_{B+}).

Step 5. If no balancing energy request is registered during the confirmed bidding period, perform appliance commutation according to the usual commutation plan (see Step 1). If the balancing energy request is registered, go to Step 6.

Step 6. Perform appliance commutations according to the Appliance Ranking List (see Step 4) and the requested balancing power.

Step 7. If deviation from the requested balancing profile is registered during the balancing energy request interval, correct the profile using the next available appliances from the Appliance Ranking List. If the balancing energy request interval is closed, go to Step 1 (update the ACP).

IMPLEMENTATION AND FIELD TESTING

Smart Metering and Control Infrastructure

The implemented Smart Grid Infrastructure is described below.

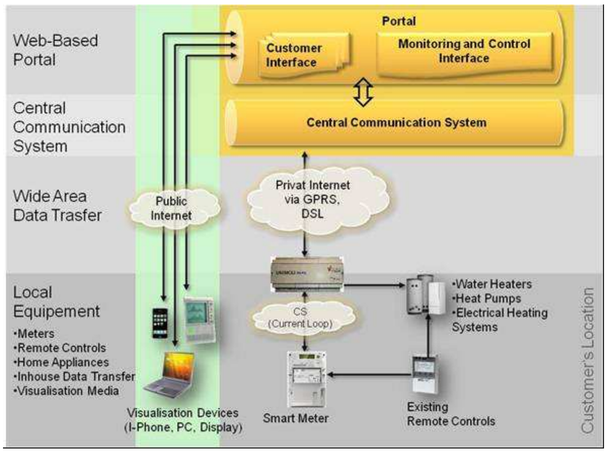

Fig. 4. Smart Grid Infrastructure, iSMART Project

The local infrastructure includes smart meters and interoperable gateways supporting two-way communication (current loop) with home appliances. Wide area information transfer is ensured by the national telecom company on a secure IP-Protocol through the GSM / UMTS network. Metering information is stored in the Central Communication System, from which data are transferred to the web-based Monitoring and Control Interface for remote access to appliances. Control signals are generated at the level of the latter according to control algorithms.

Some of the tests, essential for the estimation of the balancing power potential of appliances, are presented below.

Maximum Time ON Test

The relais of an appliance is switched on during the period of an expected minimum water temperature (e.g. between 1:00 and 4:00 a.m.) until the water heater thermostat switches off. Taking into account the specific water heater volume, it is possible to estimate the average minimum heating time needed to attain the operational temperatures range.

Minimum Time-OFF Test

For this test, the appliance relais is switched on as for the regular loading cycle and stays in this state until the following thermostat switch-on. The average interval registered is the minimal average cooling interval for the condition of the previous regular full load heating. This interval can also be measured for different durations of the heating cycle throughout the day.

Daily hot water use profile test

For this test, the appliance relais is switched on during one complete daily operation cycle. The intervals between thermostat switching are correlated with the water cooling due to the actual hot water use, from which the average daily hot water use curve can be derived.

Field testing and expected results

Field tests for this pilot-project will be conducted during Q3 and Q4, 2011. The expected results are related to the validation of the control algorithms, taking into account a large number of thermal appliances distributed across the power supply area, as well as the quality of state estimation techniques.

CONCLUSIONS

In this paper, we presented the novel approach to the residential thermal appliances, such as water heaters, heat pumps and electrical heating systems, allowing the participation of these appliances in the ancillary services markets as pool providers of tertiary reserve.

We outlined the smart grid infrastructure used for flexible load control implementation and presented the developed control algorithms, while explaining the rules of Swiss tertiary reserve market operation.

These developments demonstrate how new smart energy products can become a powerful instrument of demand response, enhancing energy efficiency, customer awareness and transparency while allowing the introduction of more CO2-neutral energy sources, ultimately generating added-value for both energy providers and consumers.

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