IMPACT OF MARKET-BASED RESIDENTIAL LOAD CONTROL ON THE DISTRIBUTION NETWORK BUSINESS

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ABSTRACT

The objective of the paper is to develop methodology to analyse the impact of market-based electric heating load control on the distribution network business. In this paper, the spot market-based load control scheme is demonstrated. The main target of the paper is to illustrate the phenomenon of space electric heating load control and its impact on the distribution network. The conflict of interests between the retailer and the DSO is demonstrated. The power band pricing scheme is suggested to be one way to solve the conflict. In the future, micro generation and energy storages could also relieve the conflict. AMR data, electricity spot market prices and outdoor temperature are used in the analyses.

INTRODUCTION

In Finland, direct load control of space electric heating has been implemented by electricity utilities as a means to avoid high peak powers already in the 1980s. At that time, the load control was carried out based on the structure of the wholesale market, and it was not based on the needs of the network. There was only a one company in each area in charge of the energy supply and distribution business. According to the wholesale tariff for electricity in 1987, the peak powers were much more expensive than the base and middle-level powers, costing about 30€/kW [1]. In case the annual peak power exceeded the level of the previous year, the company had to pay a higher rate for electricity procurements during the following several years unless the load level approached the peak power level. That is why the utilities had strong motivation to avoid new peak powers. The load control of electric space heating has demonstrated significant potential to cut peak powers during cold winters and has delivered financial benefits to the business. However, after liberalization of the Finnish electricity market in 1995, the retail and distribution sectors have been separated, and as a result, a DSO's business is no longer dependent on electricity procurements. The structure of the wholesale market has changed from capacity-based payments to energy-only payments, and the incentive for the direct load control of space electric heating has disappeared.

In the emerging smart grid environment, the need for load control has re-emerged. Because of the growing electricity consumption and an increase in the energy cost, the electricity market prices are steadily growing. In addition, the volatility of prices has become more frequent over the recent years primarily because of cold winters, intermittent renewable generation and lack of local generation. In such a market environment the electricity retailer is exposed to a risk of volatile market prices. Therefore, the focus of the retailer's business has been turned to the portfolio optimization strategy. Such tools as long-term hedging and trading in the short-term markets have been used up to this moment. In today's smart grid environment, controllable distributed energy resources (DER) also present a potential tool for the retailer's optimization strategy. The DER may include load control, micro generation and energy storages in the strategy. The focus of this paper is to present space heating load control from a retailer's perspective and analyse its impact on the load curve. In the market-based load control, the target of the retailer is to shift the amount of energy from a high-price to a low-price hour. This certainly has an impact on the power at the hour when loads are disconnected and in the following hours. The power when the heating loads are reconnected is called 'payback power' and the recovering energy 'payback energy'. The payback effect of electric heating load control has been studied in the literature already for several decades. In the literature, this phenomenon has also been referred to as 'cold load pick up' [2].

In this paper, the methodology to assess the impact of market-based load control on the distribution network is presented. The factors that affect the scope of the conflict of interests are discussed. The phenomenon of electric heating load control is described, and an optimization scheme of the load control based on spot prices is presented. The methodology has been tested on actual measured data of an urban feeder.

ELECTRIC HEATING LOAD CONTROL

The payback term refers to energy and power during the hour when restoration of electric heating storage takes place after the disconnection period. The payback power and its duration depend on the insulation of houses, outdoor temperature and duration of disconnection. Unlike other domestic loads, an electric heating load control causes a payback after reconnection because of the restoration of heat losses during the control period.

Modelling the payback power

In this section, payback power is described mathematically. For simplicity, the payback energy is presented in the form of a triangle (Fig.1).

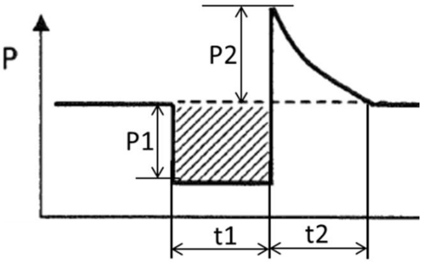

Figure 1. Illustration of the payback phenomenon

The payback power curve can be described by the equation

$$P(t) = P_2 - \frac{P_2}{t_2} * t \quad (1)$$

Disconnected energy during the load control hour:

$$E_{contr} = P_1 * t_1 \quad (2)$$

Payback energy to be recovered:

$$E_{payback} = \frac{1}{2} * P_2 * t_2 \quad (3)$$

where

- P_1 controllable heating power, kW
- t_1 duration of disconnection
- P_2 exceed power at the moment when heating loads are turned on, or payback power, kW
- t_2 duration of energy recovery, i.e., time in which all required heating energy is recovered. For simplicity, in this paper it is assumed to be 30 min, according to the measurements from [1].

The load control has been executed during a winter period for temperatures below zero, when the peak powers are high, and thereby also the risk for exceeding them is high. In order to model and analyse the payback phenomenon, the electric heating part of the total load and its dependency on the outdoor temperature have to be estimated. Fig. 2 illustrates the distribution of hourly powers of customers with electric heating loads depending on the outdoor temperatures. The variation of powers is due to daily (day and night) and weekly (weekday and weekend) variation in consumption. The dependency holds for the case distribution feeder and allows to roughly estimate the hourly heating demand for the whole period of load control, in this case one year. It is assumed that there are no space heating loads when the temperature is above +10°C. Using this assumption and the obtained dependency, the equation for hourly heating powers depending on the outdoor temperature can be formulated as

$$P(T) = P(T = +10°C) - k * T \quad (4)$$

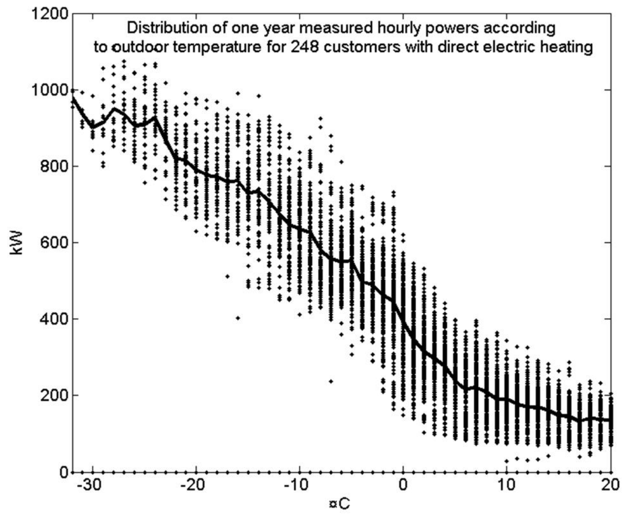

Figure 2. Distribution of hourly powers

where

$P(T=+10°C)=190\ kW$	average power when the outdoor temperature is +10°C;
$k = \frac{\Delta P}{\Delta T} = 17.8\ kW/°C$	angle of the curve line for the case feeder
T	outdoor temperature, °C

MARKET-BASED LOAD CONTROL

In this section, the generation of load control signals based on the day-ahead spot prices is presented. The control period is assumed to be a winter period so that the effect on peak powers can be estimated in the long term.

Optimization function

The data needed for the load control simulation of space electric heating include outdoor temperatures, electricity spot market prices and electricity consumption forecasts. Load control signals for customers are formed based on spot market price forecasts for the day-ahead. The electricity retailer estimates the heating demand at every hour based on outdoor temperature forecasts for the next day. The forecasted heating demand provides the information for the retailer about the controllable power on an hourly basis. Based on this, the retailer bids electricity demand for the next day according to the spot prices. The objective of the retailer's portfolio optimization is to minimize the electricity procurement costs from the spot market by shifting the energy from high-price to low-price hours. The energy cost savings maximization function can be presented as

$$\text{Esavings} = \max \int_0^T (E_{contr}(t) \cdot P(t) - E_{payback}(t+1) \cdot P(t+1))dt \quad (5)$$

E_{cost}	energy cost during a period T, €
$E_{contr}(t)$	controllable energy during the hour t, MWh
$E_{payback}(t+1)$	recovered payback energy at the hour t+1, MWh

$P(t)$ price at hour t on the electricity spot market, €/MWh

According to equation (5), energy cost savings are the higher, the larger is the price difference between the adjacent hours. The main idea of the price difference approach is that the load control takes place if the price difference between the following hours is larger than the marginal cost of the load control. Therefore, the frequency of load control events depends on the volatility of spot prices and the cost of the load control. The marginal value of the load control cost depends on the cost of the home automation technology, information communication technology (ICT), the retailer's hedging state in the long term and the frequency and number of load control events. In this paper, the cost of load control is assumed to be a fixed value, the study of which is beyond the scope of this paper.

Price difference approach

The price difference approach dictates the following rules to be implemented on the market-based load control:

1. All controllable heating power is turned off at the hour when the price difference between that hour and the following hour is higher than the value given for the load control cost.
2. It is not allowed to disconnect the load during the hour of load reconnection for the sake of customer's comfort. In case the price difference is high enough also between the following couple of hours, an optimum disconnection combination has to be found. The iterative process generates all the possible combinations of disconnections and selects the one with minimum energy costs according to equation (5).

However, optimization is not the main topic of this paper, but the above-mentioned simple principles demonstrate the operations taken by the supplier and leading to a possible conflict of interests with the DSO (Fig.3).

IMPACT ON THE DSO

The space heating load control can deliver significant benefits for the retailer's portfolio optimization problem. However, energy shifting impacts the load curve profile and poses challenges for the distribution grid and company business. Namely, the distribution grid is exposed to a risk of new peak powers as a result of market-based load control, which results in a conflict of interests between the two parties. The payback power is the parameter that characterizes the conflict of interests. The conflict of interests, or a new peak power generated as a result of the market-based load control, can be characterized by three parameters:

1. The excess of annual peak power, kW
2. Duration of peak power, min
3. Frequency of peak power, times / year

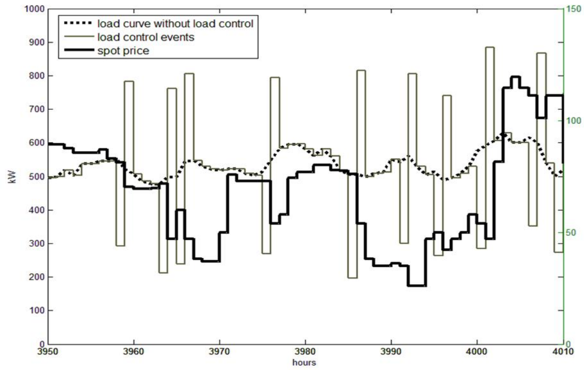

Figure 3. Example of spot price-based load control for 248 customers with direct electric heating loads during 60 hours

The short- and long-term objectives of the DSO are different. On the short-term scale (0–168 h), one target is to keep the quality of supply within the set limits. This means that voltage has to be kept within the upper and lower limits in all nodes of the distribution network, and the power flowing through the transformers, cables, overhead lines, and other network components must not exceed the maximum values. The network company also aims at minimizing energy losses. Mathematically, the short-term goals of the DSO can be presented by the following equation within technical constraints (voltage drop, thermal limits):

$$\min C_{ope} = \int_0^{168} (C_{loss}(t) + C_{outage}(t))dt \quad (6)$$

where

$C_{ope}(t)$ operational costs at hour t, €
$C_{loss}(t)$ loss costs at hour t, €
$C_{outage}(t)$ outage costs at hour t, €

From the long-term perspective (T =40 a), the objective is to minimize the total costs within the same voltage and power constraints:

$$C_{tot} = \min \int_0^{T} (C_{invest}(t) + C_{loss}(t) + C_{outage}(t) + C_{maint}(t))dt \quad (7)$$

where

$C_{invest}(t)$ investment costs, €
$C_{maint}(t)$ maintenance costs, €

The network company's primary target is to reduce investment costs as a result of peak power reduction.

Power band pricing scheme

The market-based load control poses challenges to the distribution network in such a way that a new peak power may occur. While the retailer and the customers are interested in the energy cost optimization, the DSO has to ensure the sufficient distribution network capacity. The present tariff structure does not allocate the costs of the network capacity in proportion to the customer's power consumption. Therefore, there is a need for a new network tariff scheme that encourages customers to keep the power under the limit they will pay for.

The power restrictions are transmitted to the customer in the form of a capacity-based tariff [3]. Its idea is that customers pay to the DSO not based on their fuse size, but based on a power limit agreed upon in the contract. The proposed power-based tariff scheme gives incentives to the customers to keep their electricity consumption under the contracted level. This will reduce the risk of new power peaks as a result of market-based load control.

Energy storages and micro generation

Micro generation and energy storages can provide another way to solve the conflict between the retailer and the DSO. This option is feasible especially in the future, when spot prices tend to increase, and at the same time, the cost of storage and micro generation units production decreases.
Micro generation at the customer's premises can enhance the load control potential and smooth the payback effect on the distribution grid. On the other side, in hours when the load level is low and the micro generation level is high, the voltage in the low-voltage networks may rise too high. In the case when spot prices are low, energy storages are charging, and if the load level at the same time is high, the overloading risk is high in the grid.

Results

The developed methodology has been implemented on an actual case urban feeder, to which customers with electric heating loads are connected (Fig. 4). The hourly power measurements have been carried out from November, 2010 till April, 2011. The assumptions for load control simulations are listed in Table 1.

Table 1. Assumptions for the load control modeling

Variable	Assumptions	
Duration of disconnection as a function of outdoor temperature	90 min	0…-10
	60 min	-10...-20℃
	30 min	< - 20℃
Duration of payback	30 min	
Payback energy	Equal to disconnected energy	
Cost of load control	5€/MWh	

Market-based control simulation results have shown that load control happened 147 times during the above mentioned period. The hourly power has exceeded the original power level in the interval from 135 to 356 kW every time load control for 248 customers takes place (Fig.5). However, the annual peak power was not exceeded because price difference at that hour was not enough for load control action and hence load control did not take place. If the payback power would have coincided with the hour of annual peak power, and power would have exceeded its level by 135 to 356 kW, additional needed investments would be:
$C_{invest} = NV * \Delta P = 1000 * (135 \div 356) = 135 \div 356k€$ assuming network value 1000€/kW for the case feeder.

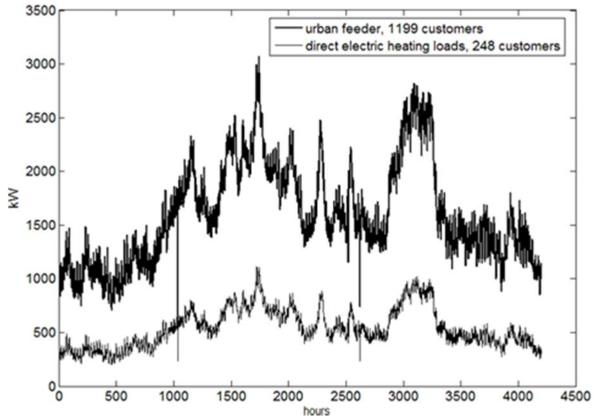

Figure 4. Load curve without load control actions

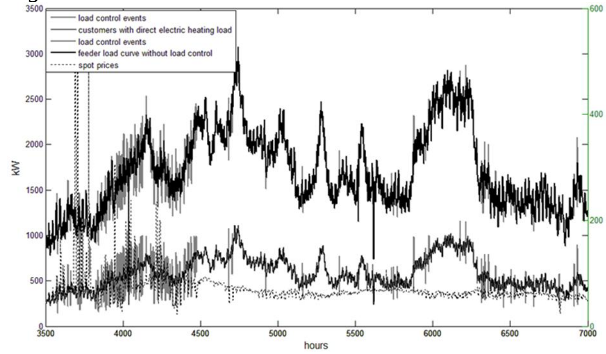

Figure 5. Load curve after load control actions

CONCLUSIONS AND FURTHER RESEARCH

The risk of exceeding the maximum annual peak power is higher during volatile market price hours and cold winter days because the payback power and its duration depend on the outdoor temperature. The impact of market-based load control depends also on the feeder topology and its ability to endure the peak power at the hour of payback. One of the further research questions is to define a reasonable size of power band for customers with future possibilities for micro generation and energy storage units, in order to ensure optimal investment costs of the DSO.

ACKNOWLEDGMENTS

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