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The Adaptive Fridge – Comparing Different Control Schemes for Enhancing Load Shifting of Electricity Demand

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Abstract

Load balancing in electricity grids becomes a more sophisticated problem by the increased availability of time-varying stochastic availability of electricity from renewable resources. Demand side management by load shifting is one attempt to cope with this problem. In this paper we discus and compare two control strategies to use the thermal storage of electrical household appliances as balancing power. For this objective we analyze a simulation model of 5000 controllable refrigerators with respect to the ability to shift their energy demand depending on parameterized external signals. Both control strategies can be used for short term reserves with delivery within 15 minutes of time, but they differ in possible shapes of the resulting load curves and in the reaction time of the controlled system.

1. Introduction to the problem to be solved

Large scale usage of renewable energies for electricity production results in time-varying stochastic availability of electricity. The growing proportion of electricity from fluctuating energy sources like wind and solar energy results in a number of problems for current systems of energy supply. Two of those are:

(1) Capacity problems for the power grid due to big amounts of electricity from renewable sources which are not consumed locally but have to be transmitted from their originating location. This problem could be addressed by building new power lines which is both costly and often hindered by political circumstances. Another technical approach to solve this problem is the incorporation of purpose-built power storage systems into the grid. However, these systems are often inefficient and expensive, both in acquisition and maintenance terms.
(2) The stable and secure operation of power grids requires a balance of electricity generation and consumption at all times (ETSO 2003). Stochastic fluctuations, caused for example by wind power production, need to be compensated either by purpose-built storage systems whose drawbacks have been noted above or by the remaining generation units. The latter solution requires power plants with short start up and adaptation times (e.g. gas turbines) which are expensive in terms of acquisition and operation.

As long as these problems are not solved, renewable energy sources will be forced to be switched off during peak availability (problem 1) and expensive and inefficient electricity production or storage is used to bridge small time spans of lacking energy supply (problem 2). In order to avoid such situations, further methods for coping with fluctuating energy sources should be envisioned. Within a project financed by a regional electricity utility in northern Germany, EWE AG, we currently analyse the load-shifting effects of residential consumers that can be obtained via dynamic pricing of electricity and other control mechanisms. By relocating loads from periods of low availability of electricity to periods of peak availability

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(Brauner et al., 2006, Klobasa and Ragwitz, 2006) both mentioned problems can be addressed. Whenever local residential consumers use more power at periods of peak availability and reduce their consumption at periods of low availability, that power will not have to be transmitted or stored by means of the utility.

2. Control of household appliances

A household's electricity consumption is shaped by the use of different types of devices and household appliances. On one hand, there is a potential for shifting electrical load by encouraging people through incentives. This potential primarily involves devices as washing machines, dish washers, or dryers. Such scenarios can be modelled and simulated with our agent based framework (Sonnenschein et al., 2006).

In this paper we will focus on the load shifting potential originating from devices that serve the purpose of keeping temperatures within given bounds. These are among others, refrigerators, water heaters, night storage heaters, and heat pumps. Devices of this type have in common, that their load shifting potential is enabled by a thermal storage system. In order to exploit their load shifting potential, no human interaction is necessary, given that a communication infrastructure from the utility to the devices is available and that the devices are equipped with suitable controllers. As an example, we study in this paper the effect of two different control schemes of exploiting the load shifting potential of refrigerators.

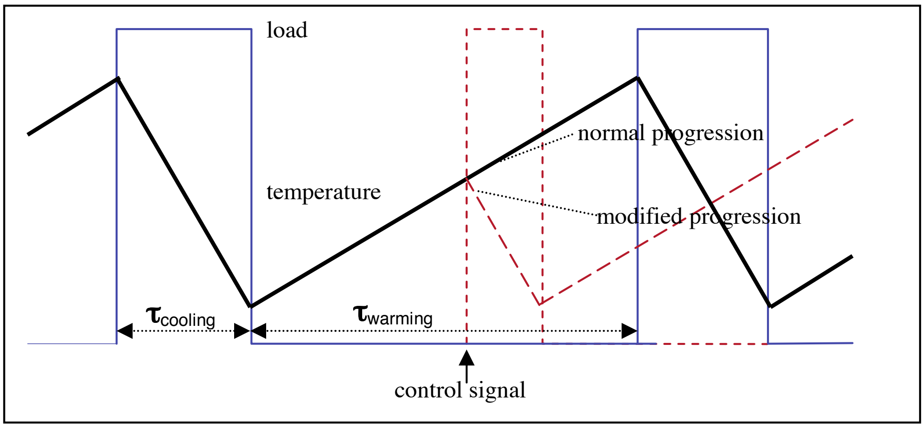

Figure 1: Principles involved in load shifting by sending a control signal

3. A model of a refrigerator

In this paper, we investigated load shifting for refrigerators as household appliances. Our refrigerator model is based on the model proposed in (Constantopoulos et al., 1991) for air conditions or heating devices. The cooling compartment temperature T

$$T_{i+1} = \varepsilon \cdot T_i + (1-\varepsilon) \cdot \left(T^O - \eta \cdot \frac{q_i}{A} \right) \quad with \quad \varepsilon = e^{-\frac{\tau A}{m_c}}$$

for an equidistant series of time steps is given by:

T_i is the cooling compartment temperature at the time step t_i, ε is the system inertia depending upon the insulation A, the thermal mass m_c (thermal storage capacity), and the time interval τ between the two time points t_i and t_{i+1}. Parameter q_i denotes the electrical power required during the last time interval depending on whether the cooling device was turned on or off, and η is the efficiency of the cooling device. T^O describes the ambient temperature which is assumed to be constant.

Because of the high number and the unknown characteristics of the load shifting devices in a residential area, the available power shifting potential is not exactly predictable. Therefore, a probabilistic approach has to be used for modelling it.

4. Basic simulation settings

We carried out discrete simulations assuming 5000 fridges all having the same appliance characteristics (same size, same insulation, rating of 70 W, same efficiency), but with different contents resulting in thermal masses equally distributed between 7.9 kWh/°C and 31.94 kWh/°C. The mean value of 15.97 kWh/°C has been calculated by using thermal capacities of food (ThermCap, 2007) and construction materials. Using this value and assuming an allowed temperature range between 5°C and 8°C the model exhibited approximately the same behaviour as fridges measured in five different households. The assumption of equally distributed thermal masses and the range of distribution is a guess due to a lack of more precise knowledge. To increase the load shifting potential, it was assumed that all fridges have the same allowed temperature between 3°C and 8°C resulting in average time spans $\tau_{cooling}$ = 30 minutes and $\tau_{warming}$ = 103 minutes depending on their thermal masses and their insulation (Fig. 1). In reality, the minimal temperature is biased towards 5°C. The fridges' temperatures at simulation begin were assumed to be equally distributed. Derived from the mean load after a day of simulation, 22% of refrigeration aggregates were assumed to be active at simulation begin. The simulation's time resolution was set to 1 minute and each simulation covered 30 hours.

5. Explored scenarios

For the investigations presented here, we simulated two basic scenarios:

(1) **Direct storage control** by signals directing participating fridges to augment or reduce the amount of energy in their thermal storage.
For this purpose, there are two control signals *load thermal storage* and *unload thermal storage*. By integrating a random number generator into the fridges' control logic, the time of a control signal taking effect can be spread over an interval. This intends to smooth edges in influenced load curves.

(2) **Timed load reduction** activated by issuing *load reduction requests* to participating fridges at a *notification time*, asking them to reduce electrical load at a given point in time called *activation time* for a requested duration (resulting in a *control interval*) with a given probability. In order to respond to these more complex controls, fridges in this scenario need to reprogram their cooling device's activity periods.

As shown in the following, these approaches differ in the degree of exploitation of load shifting potentials. Furthermore, they require different levels of intelligence and processing capacity at the device level and at the signalling instance's level.

6. Fridge controller logic and complexity

Any fridge appliance controller has to keep its cooling compartment temperature between a minimum temperature T_{min} and a maximum temperature T_{max}. This *basic temperature constraint* has to be satisfied at all times regardless of external control signals. The system inertia has got to be re-evaluated by the fridge controller regularly, based on the duration it takes for achieving a defined drop in temperature.

A simple controller as needed for direct storage control is based on the following logic: It receives a *load thermal storage* signal or an *unload thermal storage* signal with an associated time spread, which describes in which time span the refrigerator has to be activated or deactivated. The controller first has to randomly choose an activation time. At that point in time, the cooling device is either switched off (unload thermal storage) or on (load thermal storage), if this will not lead to a violation of the *basic temperature constraint* based on the controller's knowledge of current compartment temperature and current system inertia.

In order to perform this task and regularly poll the temperature sensors the controller must be equipped with a real time clock. Furthermore it must have a communication interface. Computing whether to activate or deactivate the cooling device at a given time point while taking into account the above control signals involves a few addition operations, two multiplications and a table lookup for retrieving the fridge's system inertia. Computing a pseudo random number using the middle square method (Naeve 1995) requires one multiplication and three shift operations. Storage requirements are low.

Computational and storage requirements for implementing a fridge controller suitable for reacting to timed load reduction signals are higher. Upon receiving a load reduction request, a cooling program must be calculated. Such a program defines when to switch on and when to switch off the cooling device and has to be based on the probable fridge state at activation time. Based on the assumption of non-changing outer temperature, system inertia and insulation, this can be sequentially calculated from the current temperature and cooling device state ahead of time. The sequence of cooling device states and temperatures traversed while calculating the probable fridge state at activation time (*reference state*) is stored as base program. If, based on the reference state, the requested behaviour cannot be sustained during the control interval, the controller has to modify the base program. To this end, it first has to calculate the maximum allowed temperature at activation time. Knowing this temperature, the base program's steps can be changed in reverse order starting at the activation time. This will result in a sequence of cooling device switch states approximating the needed temperature at the activation time as good as possible.

In the worst case, this computation affords to calculate $\tau_{cooling}/timebase$ steps, where *timebase* designates the length of the controller's single control step. So, the computational complexity is given by O(n), where n is the minimum of $\tau_{cooling}/timebase$ and the number of time steps between notification time t_{notify} and activation time. In addition, a controller suited for scenario 2 must provide storage for the cooling device program and for temperature time series. For implementing an embedded controller for real fridges a linear approximation of a fridge's temperature development might be considered.

7. Simulation results

Filling up thermal storages augments electrical load. Emptying storages reduces electrical load. Figure 2 gives an overview of the load characteristic resulting from thermal storage manipulation. At a given point in time t_{notify} (not shown in the figure), a control signal is issued which instructs fridges to fill up their thermal storage either with the purpose of increasing electrical load or with the purpose of maximising load shifting potential for a later point in time. To achieve this, the refrigerators start to fill their thermal storage at latest at time $t_{prestart}$. This will result in a load peak during period $\tau_{preload}$. No load peak will occur, whenever an *unload thermal storage* signal with spread 0 is issued.

The preload period is followed by a period of load reduction denoted by τ_{reduce}. During this period, cold stores are emptied. The length of the load reduction interval, the minimum load reduction, and the timing of load reduction depend on the control signals and their parameters. Note that a period of load reduction will occur even some time after a *load thermal storage* signal has been given. This is affected by the utilization of the energy in the devices' thermal storage.

In the scenarios described here, the shifting of electrical load is achieved by synchronising the fridges' thermal storages to reach either a maximum temperature or a minimum temperature during a given period of time or at a well defined point in time. Thus, after a maximum time of load reduction, cooling devices will have to be switched on. Without further control, the previously achieved synchronization leads to an oscillating electrical load. $\tau_{firstosc}$ denotes the duration of the first peak in electrical load following the load reduction.

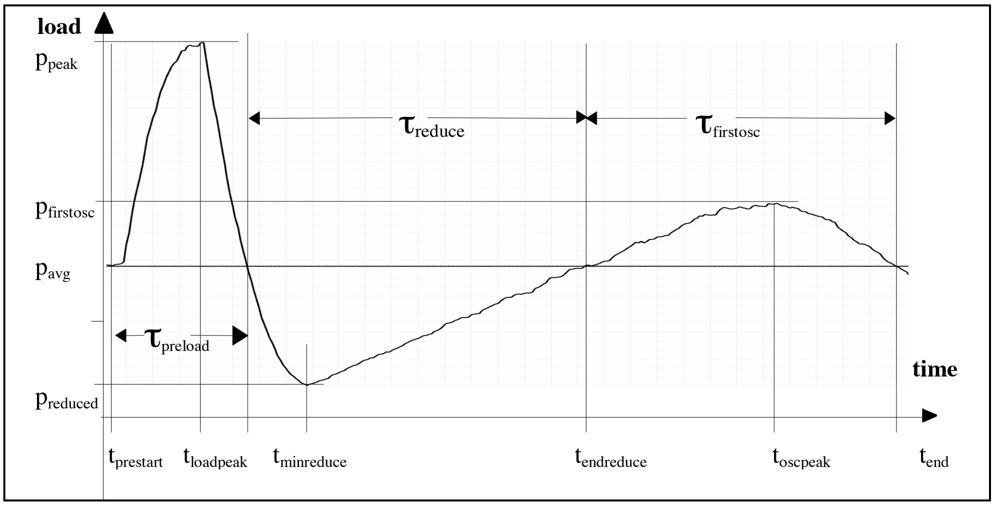

Figure 2: Electrical load evolution of 5000 devices after either issuing the *load thermal storage* signal at $t_{prestart}$ or a *unload thermal storage* signal at t_{notify} (not in the diagram, located some time before $t_{prestart}$)

Table 1: Terms to describe load shifting characteristics

p_{avg}	Average load during simulation run without influence of control signal
$\tau_{preload}$	Time span from begin of preloading to end of preloading
$t_{loadpeak}$	Time of maximum power consumption during preloading
p_{peak}	Maximum power consumption during preloading
τ_{reduce}	Time span of reduced power consumption (compared to non-signal scenario)
$t_{minreduce}$	Time of lowest power consumption during load reduction
$p_{reduced}$	Lowest power consumption during load reduction
$\tau_{firstosc}$	First time span of increased power consumption during oscillation
$t_{oscpeak}$	Time of first oscillation peak
$p_{firstosc}$	First oscillation peak load

7.1 Observations from simulated scenarios using direct storage control

First, we conducted 100 simulation runs with the *load thermal storage* signal and spreads of 0, 10 minutes, 20 minutes, …, 60 minutes, each. The analysis of the simulations results shows load reductions at least 50% for a time span of approximately one hour. However, it is not possible to achieve a 100% load reduction using this signalling type. The earliest time of availability of load reduction depends upon the spread. The delay between sending the control signal and the end of $\tau_{preload}$ is 45 minutes at minimum.

A peak load of maximum 2 p_{avg} can be sustained for a duration of 8 minutes starting five minutes after issuing the signal (spread 0) up to a duration of 20 minutes starting 45 minutes after the signal has been issued (spread 60).

Analogous experiments using the *unload thermal storage* signal allowed for an immediate load reduction to greater or equal $0.1 \cdot p_{avg}$ lasting for 15 Minutes without any preload peak.

7.1.1 The spread parameter's influence on load shifting

We investigated the influence of the spread interval in with respect to load reduction and load increase that can be achieved by issuing a *load thermal storage* signal. Augmenting the spread interval by 10 minutes delays the beginning of τ_{reduce} by approximately 5 minutes and increases $p_{reduced}$ by about $0.005 \cdot p_{avg}$. The duration of τ_{reduce} is not influenced by the spread. However, spread influences the characteristic of load reduction that can be achieved as indicated in the following table:

Table 2: Spread interval versus reduction interval length

Spread [Minutes]	100% red. [Minutes]	90% red. [Minutes]	75% red. [Minutes]	50% red. [Minutes]	25% red. [Minutes]	10% red. [Minutes]
0	0	11	23	61	97	111
10	0	10	23	60	97	112
20	0	3	23	59	96	112
30	0	0	21	57	94	112
40	0	0	16	55	93	110
50	0	0	3	53	90	109
60	0	0	0	48	87	107

Increasing the spread reduces the oscillation peak, slightly increases the start frequency of the oscillation, and reduces the peak power consumption p_{peak}.

7.2 Results of simulating timed load reduction

In the described setting with *timed load reduction* the largest possible power reduction, $p_{reduced} \approx 0$, can be sustained for a period of 15 minutes given a notification time of 10 minutes. Given a notification time of 20 minutes, $p_{reduced} \approx 0$ can be sustained for the duration of 47 minutes. The maximum duration of perceivable load reduction is 123 minutes. This value can be obtained using a minimum notification time of 110 minutes and a requested reduction interval of at least 120 minutes. The following sections give some information about load reduction parameters' influence on the load reduction curve.

Notification time

An earlier notification time entails an earlier beginning of $\tau_{preload}$. This only slightly influences $t_{loadpeak}$, and does not significantly influence p_{peak}. However, notification times over 50 minutes result in $t_{loadpeak}$ being delayed almost to the beginning of $\tau_{reduced}$ and in a significantly lower $p_{firstosc}$. Generally, longer notification times tend to stabilize $t_{oscpeak}$.

Control interval

Increasing the control interval leads to an earlier begin of $\tau_{preload}$. It also heightens p_{peak} (up to the summed rating of all fridges which is about $4.5 \cdot p_{avg}$) and shifts it closer to activation time. Furthermore this increases $p_{firstosc}$, reduces the oscillation's start frequency and also $\tau_{firstosc}$ which in turn leads to a longer overall oscillation period. Generally, longer control intervals lead to a later occurrence of $t_{oscpeak}$. Those late occurring oscillation peaks require shorter notification times for stabilisation than oscillation peaks resulting from shorter requested reduction intervals.

One specific control interval length seems to be specific to the system and leads to a stable, predictable behaviour with respect to oscillation, such that the chosen notification time is only of minor influence. As a consequence, that specific control interval length should be chosen in case of spontaneous need of *timed load reduction*.

Participation ratio

Both, $p_{preload}$ and the $p_{reduced}$ linearly depend on the participation ratio. Furthermore, the probability of oscillation increases with higher participation ratios. For participation ratios ≥ 0.4 the oscillation probability stays close to 1. $t_{firstosc}$ occurs slightly later for smaller participation ratios. However, in case of a specific reduction interval, participation ratios exhibit no influence on oscillation peak timing. The maximum achievable value for $\tau_{reduced}$ only depends upon the participation ratio, if it is less than 0.2.

8. Conclusion

Let us first state some conclusions from the observations given above:

- Both, timed load reduction and direct storage control can be used as short term reserves with guaranteed 100%-delivery within 15 minutes time. The *unload thermal storage* signal of direct storage control can even be used as balancing energy with immediate delivery.
- Timed load reduction (timed load augmentation) has the drawback of needing more powerful and expensive controllers. However, it enables a more precise time control of load shifting due to the controller's possibility of predicting a future fridge state.
- Timed load reduction should be used in order to maximise load reduction both in level and duration. The participation ratio parameter allows to scaling the reduction level exactly.
- Use direct storage control whenever immediate response is required.
- When reducing load with help of direct storage control signals, it seems sensible to use a spread of 30 minutes. This increases the time to minimal load reduction by about 15 minutes compared to a scenario without spread. However, at the same time p_{peak} can be reduced to $1.62 \cdot p_{avg}$ compared to $3.48 \cdot p_{avg}$ in a scenario without spread.

As a general conclusion we can state, that the operating conditions of refrigerators result in a rather small and varying time span (30-60 minutes) for load shifting per device. But the thermal storage of large number of refrigerators is well suited for short-time balancing. Looking for larger time spans we would have to consider electric boilers, off-peak storage heaters, or freezers. On the level of detail needed for the analysis on hand, the models of those devices differ from our refrigerator model only in terms of parameterisation.

Reaction capability to single signals both in the models and in future devices can be realised with a minimum amount of computing power. Adaptive fridges could thus very likely be based on controllers commonly used in some of today's types of household appliances if these fridges become equipped with an interface, e.g. for power line communication. More computing has to be done at the utility level in order to decide when to send signals to which households in order to achieve desired load-shifting.

9. Open issues and further work

The presented work is only a first attempt to analyze the balancing potential of cold and heat storage in the grid. Further work should include the following aspects:

- The state awareness of fridges in the scenario of timed load reduction should lead to energy savings compared to direct storage control due to the minimization of 'overcooling'. This aspect has not yet been analysed.
- In order to keep the system controllable, it is desirable, to reduce both the height of the oscillation peak and its duration, this means oscillations after load reduction have to be damped.
- In this work, we analysed scenarios with single control signals being sent. Adaptation to a desired load curve could also be achieved by sending a time series of varying energy costs to fridge controllers. A sequence of control signals minimizing energy costs could be derived from this time series. Implementing that sequence would amount to calculating a program meeting the different control signals' requirements on a best-effort basis.
- The use of load shifting is not limited to augment or decrease load during a given period of time. By grouping thermal storage devices and activating these groups using different control signals, it should be possible to exactly compose a desired load curve which could e.g. be used to compensate the starting behaviour of smaller, dynamic power generation units and thereby use the presented approach for realising virtual power plants.

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