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Modelling and evaluation of control schemes for enhancing load shift of electricity demand for cooling devices

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ABSTRACT

Load balancing in electricity grids becomes a more sophisticated problem by the increased availability of time-varying stochastic supply of electricity from conversion of renewable resources like wind or sunlight. Due to the fact that large quantities of electrical energy cannot be stored easily, demand side management by shifting electrical loads is one attempt to cope with this problem. In this paper we discuss and compare two types of control signals to use the thermal storage of electrical household appliances as balancing power. As the system of our research consists of a high number of controllable refrigerators with independent parameters and behaviour, we investigate the synergetic behaviour by a simulation model. For this objective we analyze a simulation model of controllable refrigerators with respect to their ability to shift their energy demand depending on parameterized external signals. We show that both types of control signals can be used for short term reserves with delivery within 15 min of time, but they differ in possible shapes of the resulting load curves and in the reaction time of the controlled system.

In addition to the simulation model we develop a model of the synergetic behaviour of an ensemble of refrigerators' reaction on control signals. This mathematical model predicts the electricity demand of ensembles of controlled appliances. As it reduces the simulation model's complexity it could be used in a sophisticated control strategy, e.g. in a model predictive control approach. The general attempt to integrate the load shift potential of cooling devices into the control of an electricity grid can probably be transferred to other electrical appliances with thermal storage capacities.

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 radiation results in a number of problems for current systems of energy supply. Two of those are as follows.

(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 or reduced in their efficiency during peak availability (problem 1), and expensive as well as 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.

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A well-known additional method to balance production and consumption of electrical energy is demand side management (DSM) (Gellings and Chamberlin, 1988). The general term DSM means all "utility activities that influence use on the customer's side of the meter". As a major focus in DSM is on energy conservation or energy efficiency (Clinch et al., 2001), by relocating loads from periods of low availability of electricity to periods of peak availability (load shifting) both mentioned problems can be addressed (Brauner et al., 2006; Klobasa and Ragwitz, 2006). Whenever 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. Particularly if customers shift their load to periods of high availability of environmentally friendly produced electricity (e.g. by wind energy converters), they may contribute to reduce the CO_2 emissions of conventional power plants that had to run in the periods of lower availability of environmentally friendly produced electricity (Friends of the Earth, 2006), and they contribute to avoid lossy and expensive storage of the electricity produced at supply peaks. This is particularly interesting in a scenario, where 20% of the total electricity supply is generated by wind energy converters as planned for the year 2020 in Germany. Klobasa and Ragwitz (2006) calculate additional CO_2 emissions of 350,000 t/a for balancing energy in this scenario. These emissions should be reduced by an appropriate demand side management.

There are several types of appliances suitable to be used for load shifting. Studies on load shifting by adaptive control of the air conditioning of buildings are known for a long time (Constantopoulos et al., 1991; Braun, 2003). Also refrigerated warehouses have been studied in its ability to support load shifting (Altwies, 1998). In principle this approach uses the thermal mass of buildings as energy storage.

In 2004 German households consumed about 140 TWh of electrical energy. This is about 27% of the entire consumption of electrical energy in Germany (VDEW, 2006). In contrast to customers from industry that often have special contracts with their utility, residential customers currently have very simple contracts for their electricity supply: besides a fixed base price for metering, etc., residential customers pay a constant price for each kWh of electrical energy they consume. Control of household appliances is affected only by the customers. Billing of electricity consumption is done usually one-time per year. Consequently, currently there are no potentials for load shifting of residential consumers.

This paper discusses a method to overcome this problem for a specific type of household appliances. A preliminary, abridged version of this paper has been published in Stadler et al. (2007).

2. Control of household appliances

Within a project financed by a regional electricity utility in northern Germany, EWE AG, we analyze potential load-shifting effects of residential consumers that can be obtained via dynamic pricing of electricity and other control mechanisms. On one hand, there is a potential for shifting electrical load by encouraging people through incentives, i.e. financial benefits for shifting loads. An introduction to dynamic pricing programs, where electricity prices vary depending on current production costs can be found in Borenstein et al. (2002). In households this load shifting potential primarily involves devices such as washing machines, dish washers, or dryers. Extensive field studies on the load shifting potential of such household appliances triggered by real-time pricing have been carried out, e.g. in Morovic et al. (2007). Detailed scenarios of load shifting caused by dynamic prices can be modelled and simulated with our agent based framework (Sonnenschein et al., 2006). This tool could in principle be used to model the scenarios of this paper, but for large numbers of devices (>2000) a more efficient modelling and simulation attempt turned out to be necessary. Modelling and simulation tools for the integrated consideration of supply by renewable energy converters (PV, wind turbines) and managed demand also exist (Born, 2001), but again they are too complex to analyze large, but quite uniform ensembles of devices.

In this paper we will focus specifically 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, air conditioners, and heat pumps. Devices of this type have in common, that their load shifting potential is enabled by a thermal storage system. With other words they allow to store electrical energy after conversion to thermal energy. In principle this is a conversion of a higher order type of energy to a lower order type, but for cooling devices this is the only common method. The situation is different for night storage heaters. Buildings can more efficiently heated by directly using primary energy sources like gas, or by using heat pumps. Consequently, night storage heaters although they also could be used for load shifting, are currently phased-out in Germany by law. Hence, the following considerations focus mainly on cooling devices.

In order to exploit their load shifting potential, no human interaction is necessary, given that the devices are equipped with suitable controllers. A detailed analysis of the principle potential of such devices for load shifting can be found in Stadler (2005). We will focus in this paper on different types of control signals for such devices and their potential effects.

As an example of such a household device we will address a refrigerator. Refrigerators and freezers of residential consumers are responsible for a demand of about 16 TWh per year in Germany (Klobasa and Obersteiner, 2006). This exceeds the accumulated demand of washing, dish washing, and drying, and results in a load shift potential of up to 800 MW only for refrigerators, which is equivalent to the supply of a large power plant.

In principal three different types of load shifting control for refrigerators are possible as follows.

1. The refrigerator senses the grid frequency that has the nominal value of 50 Hz in Europe. When demand exceeds supply, the frequency falls, when supply is over demand, the frequency rises. Depending on a measured difference from the nominal value of the frequency, the refrigerator can decide to precool by starting the compressor or to delay the activation of the compressor for a short-time. This control type is suggested, i.e. by Dynamic Demand (2005). Its advantage is a low price of the additional controller, because no communication between the utility and the device is necessary. On the other hand there is no way to integrate the devices into an intended schedule – the devices act completely autonomously.
2. Given a communication infrastructure between utilities and households, a refrigerator can be scheduled by a household controller integrated, i.e. into a set-top box, an Internet gateway, or a smart meter. The household controller computes a schedule for appropriate device's activities in its specific household depending on dynamic price information given by the utility. This method allows to integrate the energy management of all household devices into one system and to retain the device's control in the household, but its drawbacks are relatively complex control strategies and the fact that effects of sent tariff information to affect the load are not completely sure for the utility.
3. Given the mentioned communication infrastructure, utilities can send control signals to the refrigerators in order to raise or reduce the demand. This allows the utility a more direct control