Active Coordination of Thermal Household Appliances for Load Management Purposes

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Abstract: In this paper, a coordination approach for thermostat-controlled household appliances is developed. Under consideration are heating and cooling devices such as refrigerators, freezers, water boilers and heat pumps, which are usually characterized by an intermittent (duty cycle) operation. Without influence from the outside, an internal hysteresis switching controller toggles the "on/off" state of a device when its temperature boundary is reached. In order to realize the approach proposed here, the devices are connected to a central control entity by two-way communication. The coordination consists of a step-wise heuristic solution of a binary optimization problem, which serves to select a number of devices in each time step that are subject to compulsory switching, i.e. toggling the "on/off" state. It allows a large group of devices to track a setpoint trajectory with its aggregated power consumption, acting like a distributed virtual energy storage, while the individual temperature bounds of the appliances are not violated. This behavior can be used for grid-control purposes, such as the provision of active power reserves. It will be shown that the group of appliances can be characterized by an approximate aggregated dynamical model consisting of a first-order differential equation together with an approximate aggregated nonlinear cost function penalizing the control actions. The developed methodology is evaluated in a numerical simulation with a small appliance cluster corresponding to a residential housing area.

Keywords: Electrical Appliances; Load Modeling; On-Off-Controllers; Load Regulation; Binary Control; Switching Algorithms.

1. INTRODUCTION AND MOTIVATION

The penetration of power systems with intermittent renewable energy sources such as wind and photovoltaic generation has been increasing rapidly during the recent years. In order to reduce greenhouse gas emissions, incentive schemes (such as feed-in tariffs) have been put into place in many countries, and renewable energy technologies tend to get cheaper over time. This suggests that the present trend will continue or even accelerate in the future, which causes the need for significant adaptation of power system operation. Although intermittent infeeds can be predicted with relatively high accuracy, which can be incorporated in the dispatch methodologies of conventional power plants, there is still a rising need for controllability of generation and/or consumption on various timescales, e.g. in order to account for the remaining infeed prediction errors.

The idea of Demand Side Management (DSM), although in principle known for decades, has been getting an increasing amount of attention during the last few years due to these developments. In its traditional form, DSM consists of the deactivation of certain loads during peak hours, e.g. through financial incentives for users (see Rasanen et al. [1995]) or remote-controlled by the electricity provider (e.g. by ripple control equipment). However, more sophisticated control tasks as e.g. the provision of ancillary services cannot be tackled with these concepts.

A number of approaches to load participation in grid control are based on a decentralized frequency-response mechanism for heating and cooling loads. The idea was already presented in Schweppe et al. [1980], and it also appears in recent publications like Short et al. [2007]. It constitutes an extension to the inherent frequency dependence of the load, which can reduce the need for primary control reserves. In these concepts, however, the impact of the control on the appliance duty cycle can be quite substantial and hard to quantify in advance. Furthermore, several studies suggest, e.g. for the German power system in Ernst et al. [1999], that the main impact of intermittent generation is not on the primary control reserves in the range of seconds but rather on larger timescales. This raises the question if the trade-off between a control contribution and the impact on the operation of a privately owned device is well-balanced in this case.

A lot of recent work in the field of non-frequency-based load management (among others Lu and Katipamula [2005], Kupzog [2006], Stadler et al. [2009]) is aimed at further increasing the controllability of heating and cooling loads. While the exploitable flexibility of the demand side is improved by the recent projects, as yet no approach is known that can impose an arbitrary curve shape, which may also be changed shortly before realization, on the aggregated active power demand of a large set of devices.

In this paper, a novel automatic load management methodology is developed which further extends the controllability of flexible loads[1]. It allows a high number of thermostat-(hysteresis-)controlled heating and cooling household appliances, equipped with two-way communication, to make an active contribution to power system control. This means that the control algorithm can freely and quickly increase or decrease the aggregated active power demand of a large group of appliances within certain limits, enabling the group to act like a virtual distributed energy storage. To avoid user comfort losses, the upper and lower temperature bounds of the appliances (switching thresholds) shall be respected at all times, and the alteration of the device duty cycle shall be kept as small as possible. Furthermore, the device must be able to function normally in the case of a communication failure.

The paper is organized as follows: section 2 briefly presents a possible communication infrastructure, while section 3 introduces a modeling framework for the appliances themselves. In section 4, steady-state properties of uncoordinated appliance groups are determined that are useful for the coordination approach, which is presented in section 5. Section 6 deals with the aggregated properties of coordinated appliance clusters, followed by numerical results in section 7. Some conclusions and ideas for further research are given in section 8.

2. COMMUNICATION INFRASTRUCTURE

During the course of the LLM project, the hardware and software for a two-way communication infrastructure is being developed, providing the link from the appliances to a control center. Within the household, the system is composed of two kinds of units: one central "Load Manager Household" (LMH) device and several "Load Manager Appliance" (LMA) units which are installed in the individual appliances, as depicted in Figure 1. Note that also a number of non-thermal appliances are shown here, which do not take part in the coordination approach outlined in this paper, but will be used in a decentralized load shedding scheme investigated in parallel. The in-house link between the LMAs and the LMH can be realized with Powerline Communication (PLC) according to Konnex PL-132. For the communication between the household and the control center, two alternatives are being considered: a low-voltage network PLC to the nearest transformer station combined with a subsequent transmission over a proprietary utility communication channel, or a TCP/IP transmission over a permanent internet connection installed in the household. For further details, see Koch et al. [2009].

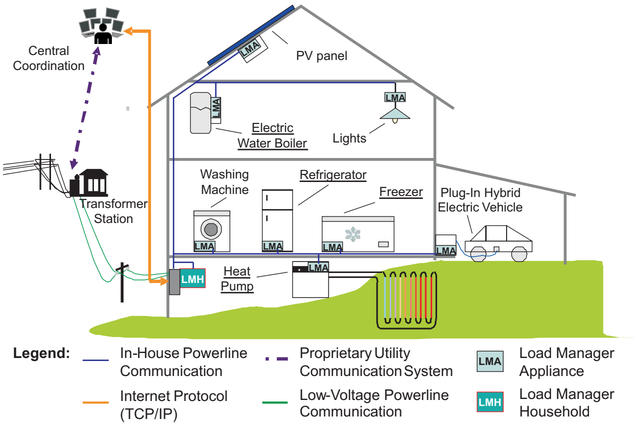

Fig. 1. Communication infrastructure in the household

3. THERMAL MODELING FRAMEWORK

In this section, a thermal modeling framework for the appliances under consideration is developed. For this purpose, a unified representation of heating and cooling devices of different nature is derived. It is assumed that all appliances are operated with a thermostat switching controller which turns the appliance "on" and "off" depending on its internal state.

3.1 Normalized expression of the appliance state

As in other known publications on thermostat-controlled heating and cooling appliances such as Bompard et al. [1996], Lu and Katipamula [2005], the dynamic state variable used here is the measured internal temperature T [°C]. In order to derive a unified description of the device state independent of the temperature level and device type, a description of the internal thermal energy relative to the ambient temperature T_{amb} [°C] can be used. This yields for cooling and heating devices:

$$E_{\text{th,cool}} = m \cdot \bar{c} \cdot (T_{\text{amb}} - T) \quad , \tag{1}$$

$$E_{\text{th,heat}} = m \cdot \bar{c} \cdot (T - T_{\text{amb}}) \quad , \tag{2}$$

where m [kg] represents the mass contained in the device and $\bar{c}$ $[\frac{\text{J}}{\text{kg}\,\text{K}}]$ the average heat capacity of the contents. The switching threshold temperatures of the appliance, T_{min} and T_{max} [°C], can be transformed similarly. The energy content E_{th} is now normalized to an interval of $[0, 1]$ using

$$E^{\text{rel}}_{\text{th,cool}} = \frac{T_{\text{max}} - T}{T_{\text{max}} - T_{\text{min}}} \quad , \tag{3}$$

$$E^{\text{rel}}_{\text{th,heat}} = \frac{T - T_{\text{min}}}{T_{\text{max}} - T_{\text{min}}} \quad . \tag{4}$$

The thermal energy of the ambiance is equal to zero in absolute terms (reference level) and usually negative in relative terms. The latter expression is obtained by substituting $T = T_{\text{amb}}$ in equations (3) and (4).

3.2 Dynamic appliance models

Now, the differential equations describing the evolution of the appliance state are introduced. Considered here are refrigerators, freezers, and water boilers.

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[1] The outlined work is part of the project "Local Load Management" (LLM) which has been conducted by a team from ETH Zurich, University of Applied Sciences North-Western Switzerland (FHNW), Atel Netz AG and Landis+Gyr since 2006. The project is financially supported by swiss*electric research*. The current project phase is called "Electricity grid security and operation taking into account distributed loads, in-feeds and storages", which commenced in 2007. Its principal goals are the development of a suitable communication infrastructure for applying a sophisticated load management scheme in private households, algorithms for coordinated appliance operation, inclusion of storages and distributed generation, decentralized under-frequency load shedding, as well as economical considerations and strategies for the regulatory or market-based introduction of Local Load Management into today's electricity systems.