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An Active Coordination Approach for Thermal Household Appliances – Local Communication and Calculation Tasks in the Household

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***Abstract*—In this paper, an approach to the coordinated operation of a multitude of household appliances with thermal inertia is presented, which can be used for power system control tasks. Appliances under consideration are cooling and heating devices, e.g. refrigerators, freezers, or electric water boilers, which are characterized by an intermittent (duty cycle) operation. A recently developed coordination algorithm for a large group of these thermostat-controlled appliances equipped with a two-way communication interface uses centrally computed switching impulses based on an "offer to be switched for a certain price" from the appliances. The price calculation on the local level requires an accurate prediction of the next switching instant triggered by the thermostat. This paper develops a framework for the communication within the household and to the outside, modeling and prediction approaches for the appliance duty cycles, and a switching price calculation method. Furthermore, the impact of the coordinated control on the appliances and requirements on the in-house communication system are discussed.**

I. INITIAL CONSIDERATIONS

The increasing penetration of power systems with intermittent renewable energy sources such as wind and photovoltaic power generation has triggered a rising interest in control techniques that use flexible demand for the support of grid control tasks normally performed by generation units. Although the idea of Demand Side Management (DSM) is not new (see e.g. [1] and [2]), a lot of recent work done in this field (among others [3], [4], [5], [6], [7], [8]) is aimed at further increasing the controllability of loads, mostly those for heating and cooling purposes, in order to make active control contributions. This is a qualitative difference to the "conventional" DSM techniques which are targeted at shifting demand from peak to off-peak hours by user incentives and enforced deactivation. Most of the recent approaches utilize some sort of price signal which causes certain appliances to either consume or not consume energy. While this increases the exploitable flexibility of the demand side, as yet no approach was proposed that is able to impose an arbitrary curve shape, which may also be changed shortly before realization, on the active power consumption of a large set of devices.

In this paper, a novel automatic load management methodology is outlined which makes a contribution to closing this gap[1]. It allows a high number of thermostat-(hysteresis-)controlled heating and cooling household appliances, equipped with two-way communication, to participate actively in 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 cycles shall be kept as small as possible.

The storage-like aggregated behavior is achieved by the following scheme: in consecutive time steps, a central coordination algorithm is used to trigger "on" or "off" switching actions in selected appliances according to a certain consumption setpoint for the entire group. For the preservation of local autonomy, an appliance shall only be switched if it "offers" to be switched for a certain price. If the switching offer is accepted by the central coordination, the "on/off" state of the appliance is toggled and the offered price is paid to the owner of the appliance as a compensation for the control contribution.

Thus, the local infrastructure in the household must implement the calculation and periodic transmission of switching price functions for a few appliances present in that household to a central coordination entity. The calculated price is variable over time, depending on the device duty cycle: it should obviously be higher when a large alteration of the normal duty cycle would be imposed by an enforced switching, and lower for only small alterations. Furthermore, the actual switching actions must be triggered based on the "acceptance" of the "offers" by the central coordination.

The goal of this paper is the development of an automatic communication and calculation concept based on the outlined ideas, which is able to run by itself in a private household. The basic idea of the time-step-wise optimization scheme running

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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 called "Electricity grid security and operation taking into account distributed loads, in-feeds and storages" commenced in late 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.

in the central coordination unit has been presented in [9], a more elaborate explanation following in [10].

This paper is organized as follows: section II discusses the necessary communication infrastructure for enabling household devices to participate in the presented Local Load Management system, while section III describes the distribution of calculation tasks and communication interfaces between the involved units. Section IV explains the modeling framework for the heating and cooling loads under consideration. Section V presents the price calculation methodology and the involved duty cycle prediction tasks, which will be demonstrated using measured appliance data. Section VI describes the impact of the coordination methodology on the local level and discusses requirements on the in-house communication system. In section VII, some results from simulation will be shown which illustrate the effect of compulsory switchings and user interactions. Conclusions and suggestions for further research are given in section VIII.

II. Communication infrastructure

One of the first questions to be answered to enable an implementation of the presented load management scheme is how to provide the required two-way communication link from the devices installed in households to a control center.

In close relation with the theoretical considerations presented here, the hardware for a two-way communication infrastructure is being developed. Within the household, it 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.

The computational tasks of these two types of units are highly dependent on the used coordination concept, which will be elaborated on later. As depicted in Figure 1, the in-house link between the LMAs and the LMH can be realized with Powerline Communication (PLC) according to the Konnex PL-132 standard (see [11], [12]). Note that in Figure 1 a number of non-thermal appliances are shown as well, which do not take active part in the coordination approach outlined here, but will be used in a decentralized load shedding scheme investigated in parallel.

For the communication between the household and the control center, two alternatives are being considered. The first is a low-voltage network PLC [13], which is of different nature compared with the in-house PLC, to the next transformer station with a subsequent signal transmission over a proprietary utility communication channel from the transformer station to the control center. The second option is a TCP/IP transmission over a permanent internet connection installed in the household.

It is important to stress that the Local Load Management approach does not depend on a specific implementation of the communication infrastructure. On the local level, different communication platforms like wireless or bus-connected systems could even be connected to the same coordination entity. The most important point is the clear definition of information interfaces between the different units and the comparability of the communication systems in terms of reliability and bit rate.

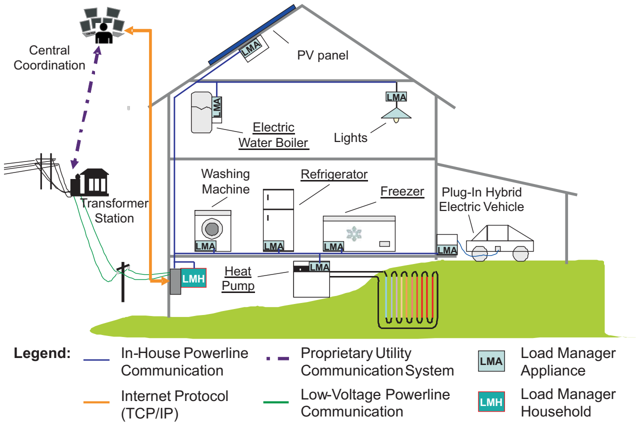

Figure 1. Communication infrastructure in the household

III. Calculation and measurement tasks

A. General requirements

Apart from the provision of a communication link, the LMA and LMH units have to fulfill a number of tasks in terms of calculation, measurements and data organization in the household. These depend largely on the rationale of the load management scheme. In the case presented here, a distinction is made between the normal operation control, where the central coordination unit plays a significant role, while the under-frequency load shedding shall be based on autonomous, decentralized behavior of the household. The second scheme is not regarded in detail in this paper. Note that the LMA unit shall be as cheap as possible, as it should be integrated in individual appliances, thus it will not possess much computational power and measurement equipment. The LMH can be a bit more costly, as only one unit per household has to be installed.

Due to these considerations, the following requirements on the infrastructure are defined:

1) In heating and cooling appliances, the LMA shall be able to alter the ”on/off” state based on an external impulse (”toggle signal”) without overriding the appliance switching boundaries.
2) The LMA must have the possibility to block the power consumption of an appliance completely based on an impulse from the LMH (”blocking signal”).
3) The LMH shall be able to perform a relatively simple identification/prediction task for the thermal appliances and some other algebraic manipulations.
4) The LMH shall measure the local frequency in short time intervals and compare these to threshold values preset by the central coordination. Based on this, it shall send a blocking impulse to the appliances in the case of an abnormal grid condition.
5) The central coordination unit (control center) has to ”close the loop” constituted by the household infrastructure together with the appliances. Its main task is to aggregate and evaluate the information from the individual appliances, trigger control actions based on optimization algorithms and enable the large group of appliances to act as a single entity.

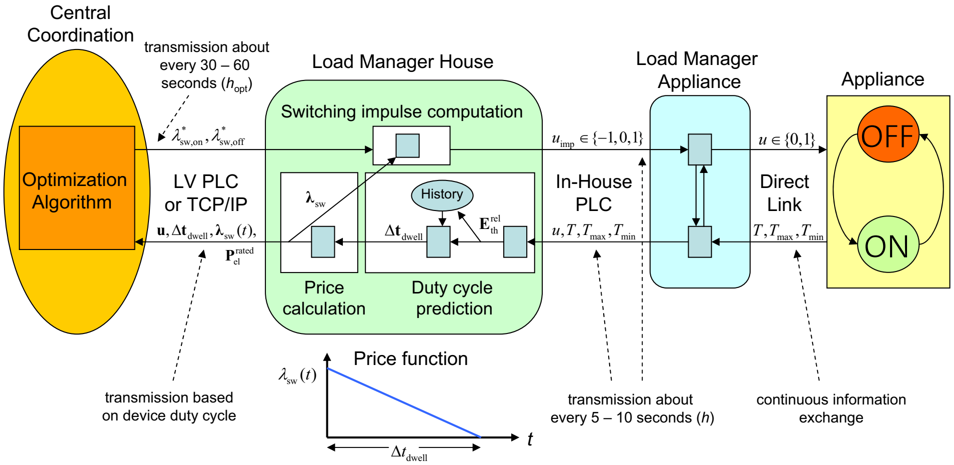

Figure 2. Calculation tasks and interfaces between the units

B. *Information flow between the units*

A concrete concept for the flow of information between the involved entities is now developed. Figure 2 displays the four involved units: the appliance, the LMA, the LMH and the central coordination entity. As shown on the right side, the LMA takes over the function of the internal switching controller of the appliance, i.e. toggling the "on/off" state u based on the measured temperature T and the desired switching thresholds T_{min}, T_{max}. The latter values can be set by the unit itself or also by the LMA. Because not much computational power will be present on the appliance level, the LMA forwards the information over the in-house communication link to the LMH in short time intervals, where the duty cycle prediction (estimation of dwell time Δt_{dwell}) and the calculation of the switching price λ_{sw} take place. The calculated price functions reach up to the next (predicted) autonomous switching instant and are transmitted to the central coordination. Note that this shall be done only when an appliance executes a switching action or when the prediction changes significantly due to user interaction, in order to reduce the need for external communication. The global coordination algorithm aggregates all the information and computes in turn "clearing prices" $\lambda^*_{\text{sw,on}}$ and $\lambda^*_{\text{sw,off}}$ for on and off switching actions in the current time step (e.g., every 30 – 60 seconds) which are transmitted to all households. The LMH compares this to the momentary switching price of its appliances and sends switching impulses u_{imp} to individual LMAs if applicable, which in turn adjust the switching state u.

C. *Protection of user privacy*

In the discussions about "smart" electricity infrastructure, concerns about user privacy and data protection have emerged which need to be addressed accordingly. Under the requirement that an individual household participating in the Local Load Management scheme should not be transparent to the operating company in terms of size, number, and state of installed appliances, an individual appliance addressing should be avoided. This is achieved by the above mentioned accepted switching ("clearing") prices, to which the appliances react autonomously. As there are two groups of appliances, one currently on that can be switched off, and another group currently off that can be switched on, two different accepted prices must be transmitted. Thus, any appliance offering a lower price than the accepted one is switched by the LMH. This avoids the need for the individualized collection of data. Furthermore, communication requirements are also far lower in a "broadcast" scheme than with individual addressing.

IV. 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.

A. *Normalized expression of the appliance state*

As in other known publications on thermostat-controlled heating and cooling appliances as [8] and [14], 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 $\bar{c}$ $[\frac{\text{J}}{\text{kg K}}]$ 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).

B. Dynamic appliance models

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

1) Refrigerator and freezer: The relative thermal energy content evolves according to

$$\frac{dE_{\text{th}}^{\text{rel}}}{dt} \;=\; -\Big(\frac{1}{\tau}+\frac{1}{\tau_{\text{open}}}d\Big)\,(E_{\text{th}}^{\text{rel}}-E_{\text{th, amb}}^{\text{rel}})+\frac{k}{\tau}\,u\,, \qquad (5)$$

where the thermal losses depend on the difference between the ambient energy level and the inside energy level. $u \in \{0,1\}$ is the binary switching input variable. The time constant τ [s], the amplification factor k [-], and the initial condition of the differential equation are determined by

$$\begin{aligned}\tau \;&=\; \frac{m\,\overline{c}}{A\,\overline{\alpha}} \quad , && (6)\\ k \;&=\; \frac{\varepsilon_{\text{th}}\,P_{\text{el}}^{\text{rated}}}{A\,\overline{\alpha}\,(T_{\text{max}}-T_{\text{min}})} \quad , && (7)\\ E_{\text{th,0}}^{\text{rel}} \;&=\; E_{\text{th}}^{\text{rel}}(t=t_0) \quad , && (8)\end{aligned}$$

with the average heat transfer coefficient $\overline{\alpha}$ $[\frac{W}{m^2\,K}]$ and the hull surface A [m^2]. ε_{th} is the coefficient of performance of the cooling aggregate (including the efficiency of the compressor), and $P_{\text{el}}^{\text{rated}}$ [W] is the rated power consumption of the appliance[2]. Stochastic user interactions (door openings) are modeled by the binary disturbance input $d \in [0,1]$ (combined with the heuristic time constant τ_{open} [s] during door-openings) and occasional variations of the time constant τ, which is linearly dependent on the mass.

2) Electric water boiler: For the water boiler, the governing differential equation looks very similar:

$$\frac{dE_{\text{th}}^{\text{rel}}}{dt} \;=\; -\Big(\frac{1}{\tau}+\frac{\dot{m}_{\text{demand}}}{m}\Big)\,(E_{\text{th}}^{\text{rel}}-E_{\text{th, amb}}^{\text{rel}})+\frac{k}{\tau}\,u\,, \qquad (9)$$

where τ, k and $E_{\text{th,0}}^{\text{rel}}$ are defined as in equation (6) - (8) and $\varepsilon_{\text{th}} = \eta_{\text{th}}$ is the thermal efficiency of the electric heating element. $\dot{m}_{\text{demand}}$ [kg/h] represents the mass flow of the water that is drawn from the boiler by the user, which is instantly replaced by fresh water assumed to enter the boiler at ambient temperature.

For all appliances modeled in the above way, a hysteresis switching controller acts on the input variable u which is expressed in the same normalized form:

$$u = \Big\{ \begin{array}{lll} 1 & \text{if} & E_{\text{th}}^{\text{rel}} \leq 0 \\ 0 & \text{if} & E_{\text{th}}^{\text{rel}} \geq 1 \end{array} \quad . \qquad (10)$$

C. Relation between thermal and electrical energy content

The relative thermal energy content, which evolves in the interval [0,1] during normal operation, represents a different span of actual thermal energy for each device between the upper and lower switching boundaries T_{max} and T_{min}. This net energy is described by

$$E_{\text{th}}^{\text{net}} = m\,\overline{c}\,(T_{\text{max}}-T_{\text{min}}) \quad . \qquad (11)$$

As the relation between thermal and electrical input power is given by

$$P_{\text{th}}^{\text{rated}} = \varepsilon_{\text{th}}\,P_{\text{el}}^{\text{rated}} \quad , \qquad (12)$$

the same can be stated for the thermal and electrical energy contents. Taking into account equations (6), (7), and (11), it is easy to show that the net electrical energy span between the two switching boundaries is

$$E_{\text{el}}^{\text{net}} = \frac{\tau}{k}\,P_{\text{el}}^{\text{rated}} \quad . \qquad (13)$$

Furthermore, it can be shown using the results from equations (1) - (4) that the electrical and thermal relative energy contents are the same:

$$E_{\text{el}}^{\text{rel}} = E_{\text{th}}^{\text{rel}} \quad . \qquad (14)$$

D. Applicability of the models

In the dynamic models presented above, all appliances are regarded as a single mass with uniform temperature distribution which evolves between the switching boundaries. However, this is not always an accurate representation of real appliances. In practice, temperature distributions can be found in storage tanks of water boilers, and the internal energy flows of cooling devices are known to be a lot more complex. As every appliance is different and a more detailed model is unlikely to yield useful information on an aggregated level, the measured temperature at the thermostat of the appliance (e.g. at the evaporator of a cooling device) is considered as the appliance temperature. In most cases, it has a first-order characteristic, the parameters of which can be identified. This implies that e.g. the mass and heat capacity of the thermal storage are "equivalent" quantities derived from observing the duty cycle of the appliance, rather than actual physical values based on first-principles considerations.

V. DUTY CYCLE PREDICTION AND PRICE CALCULATION

The used approach for predicting the next autonomous switching instant and the resulting calculation of a price offer by the individual appliances for compulsory switching will be discussed in this section. As outlined in section III, this calculation will take place in the LMH. A discrete sample rate h is used for the collection and storage of measurements. However, the prediction does not necessarily have to be performed in every time step. All computations are conducted individually for each appliance.

A. Prediction approach

Considering the modeling in section IV, the following prediction approach is adopted: a parameter fit of a first-order differential equation is used to represent the dynamics of the appliance state $E_{\text{th}}^{\text{rel}}$, from which the dwell time Δt_{dwell} is calculated. The identification yields the parameters τ and k as in equation (5), which are obtained by using a least-squares

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[2] For simplicity, the rated power is regarded as constant here, although it actually depends on the supply voltage. In the cooling appliances, active power transients during the "on" phase due to thermodynamic effects are also neglected. If desired, corresponding duty-cycle and voltage dependent factors can be included in k.

parameter identification technique. The dynamics of water boilers is here identified in the same way as the dynamics of cooling appliances, the disturbances d and $\dot{m}_{\text{demand}}$ are set to zero. For the identification, the *Matlab* function `pem` is used.

Special attention has to be paid to the constant offset $\frac{1}{\tau} \cdot E^{\text{rel}}_{\text{th,amb}}$ in the differential equation, which normally can be calculated by substituting $T = T_{\text{amb}}$ in equations (3) and (4). However, this will not always yield useful results. As in the case of cooling appliances the evaporator temperature is measured, the ambient temperature T_{amb} does not necessarily define the thermal equilibrium of the dynamical system. This is because the evaporator exchanges energy with compartments of the cooling appliance, which are much colder than the ambient temperature. Obviously, the eventual thermal equilibrium of the whole appliance will always be at ambient temperature, but this equalization process will be in general much slower than the transfer of heat within the appliance.

The problem is tackled by treating the offset referring to the thermal equilibrium as an input-level offset u_{level}, which can also be identified by least-squares estimation using the `pem` option `InputLevel`. This way, no first-principles knowledge about the thermal equilibrium has to be employed. The transformation is done in the following way:

$$\frac{dE^{\text{rel}}_{\text{th}}}{dt} = -\frac{1}{\tau}E^{\text{rel}}_{\text{th}} + \frac{k}{\tau}(u + \underbrace{\frac{E^{\text{rel}}_{\text{th,amb}}}{k}}_{u_{\text{level}}}) \quad . \tag{15}$$

Having obtained u_{level}, k, and τ from the identification, the ambient relative energy can be calculated using

$$E^{\text{rel}}_{\text{th,amb}} = k \cdot u_{\text{level}} \quad . \tag{16}$$

Finally, the estimated dwell time is obtained in each prediction time step through an explicit solution of the governing differential equation separately for the "on" phase ($u = 1$) and "off" phase ($u = 0$):

$$\Delta t_{\text{dwell}} = -\tau \cdot \ln \frac{E^{\text{rel}}_{\text{th,end}} - E^{\text{rel}}_{\text{th,amb}} - k \cdot u}{E^{\text{rel}}_{\text{th}} - E^{\text{rel}}_{\text{th,amb}} - k \cdot u} \quad , \tag{17}$$

where $E^{\text{rel}}_{\text{th,end}}$ is the switching boundary which will be reached in the current switching state. This is $E^{\text{rel}}_{\text{th}} = 1$ in the "on" phase and $E^{\text{rel}}_{\text{th}} = 0$ in the "off" phase, thus $E^{\text{rel}}_{\text{th,end}} = u$. The full dwell time of one entire "on" or "off" phase $\Delta t^{\text{full}}_{\text{dwell}}$ can be obtained by substituting $E^{\text{rel}}_{\text{th}} = 1 - u$ in equation (17) which represents the (autonomous) switching threshold where the current phase started.

To verify the proposed technique, measured data from a real cooling appliance with a rated power of 90 W is used. The evaporator temperature bounds are set to $T_{\text{min}} = -21.5$ °C, $T_{\text{max}} = +2$ °C. The data is sampled with a step size of $h = 5$ s, which is quite a high temporal resolution considering the appliance dynamics. For the identification, a moving window of the five previous hours is regarded in each time step and the curve is smoothed with a moving average window of 20 samples. Figure 3 shows the dynamics $E^{\text{rel}}_{\text{th}}$, the switching variable u, and the comparison of the computed dwell time (normalized with the full dwell time of the current "on/off" state) at each time instant with the actual normalized dwell time. It can be seen that the result from the identification is quite noisy, but it lies relatively close to the real value. As the dwell time evolution over time should be exactly linear, a linear regression on the computed dwell time during the current "on/off" state can be used to eradicate the noise.

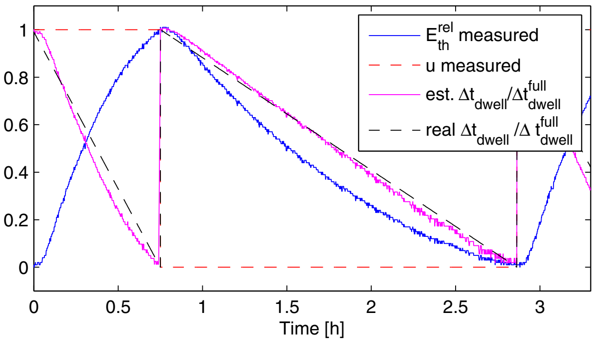

Figure 3. Comparison of predicted and real dwell time

Note that the solution of the prediction problem is not restricted to the method presented here – any other method that yields an accurate estimation of the upcoming switching instant can be used within the framework of Local Load Management. One example is using a feed-forward neural network which regards the instantaneous values of $E^{\text{rel}}_{\text{th}}$ and u as an input to calculate the output Δt_{dwell}. As the actual dwell times can be calculated easily when the appliance behavior is observed, the neural network can be trained by using this historical data.

B. *Price calculation*

With the information obtained from the prediction, a price function over time is determined, which depends (here linearly, but also quadratically is possible) on the remaining dwell time normalized with the full dwell time. Obviously, the price has to be equal to zero in the autonomous switching instant itself. The price function c_{sw} [cent] is designed here in the following way:

$$c_{\text{sw}}(t) = \lambda_{\text{sw}}(t)\, P^{\text{rated}}_{\text{el}} = \frac{\Delta t_{\text{dwell}}(t)}{\Delta t^{\text{full}}_{\text{dwell}}(t)}\, \lambda_{\text{P}}\, P^{\text{rated}}_{\text{el}} \quad , \tag{18}$$

where $\lambda_{\text{sw}}(t)$ [cent/W] is the normalized switching price offer by the appliance depending on the (predicted) remaining dwell time Δt_{dwell} of the appliance in its current "on/off" state, the (predicted) overall dwell time $\Delta t^{\text{full}}_{\text{dwell}}$ including the time already elapsed in the current state, and a fixed price constant λ_{P} [cent/W]. It is scaled by $P^{\text{rated}}_{\text{el}}$ [W]. Note that the dwell time becomes negative if the appliance state moves away from the switching boundary it should approach, e.g. because of user interaction. In this case, the price shall be adjusted to ∞ (or a high numerical value) in order to avoid any compulsory switching actions. The same holds for an abnormal state $E^{\text{rel}}_{\text{th}} \notin [0, 1]$.

VI. THE INDIVIDUAL HOUSEHOLD APPLIANCE IN A COORDINATED GROUP

In this section, the impact of the global coordination algorithm on the local level will be discussed. Furthermore, an estimation of the requirements on the in-house communication bit rate imposed by the control scheme will be given.

A. Impact of the control on the appliances

As outlined in [10], the coordination algorithm has a shortening effect on the appliance duty cycles. The algorithm runs in the control center with a step size of h_{opt}, which is different from the in-house communication step size h. This is because the in-house information exchange serves the purpose of identifying the thermal dynamics of just a few appliances, while the central coordination calculates the compulsory switching action which has to take into account the whole amount of appliances in the group.

For assessing the duty cycle shortening, two situations have to be distinguished. First, the central optimization algorithm will compulsorily switch all appliances that would switch by themselves in the upcoming optimization time step. This serves to prevent appliances from switching asynchronously between the optimization time steps, which would cause a change in active power consumption that cannot be influenced by the coordination. These compulsory switchings lead to a maximum duty cycle shortening equal to the value h_{opt} per switching action. If h_{opt} assumes a value around 30 s, the duty cycle shortening caused by the need to maintain synchronism is relatively insignificant.

The second cause of duty cycle shortening are actual control actions on the current active power consumption of the whole group of appliances. As shown in [10], the group of appliances under the coordination regime can be described approximately by the differential equation

$$\frac{dE_{\text{el}}^{\text{total}}}{dt} = -\frac{1}{\overline{\tau}}\left(E_{\text{el}}^{\text{total}} - E_{\text{el,amb}}^{\text{total}}\right) + P_{\text{el}}^{\text{total}} \quad , \tag{19}$$

where $E_{\text{el}}^{\text{total}}$ is a representation of the total electrical energy stored between the temperature bounds of the appliances, $E_{\text{el,amb}}^{\text{total}}$ is a constant reflecting the electrical energy dissipation because of thermal losses of the appliances, $\overline{\tau}$ is an aggregated time constant and $P_{\text{el}}^{\text{total}}$ is the aggregated electrical power consumption of the group. The initial condition of the differential equation is $E_{\text{el,0}}^{\text{total}} = E_{\text{el}}^{\text{total}}(t = t_0)$.

The steady state of equation (19) yields a relation between the steady-state power consumption and storage level of the group. Imposing a different power consumption will "charge" or "discharge" the aggregated thermal storage constituted by the appliances. Figure 4 depicts the approximate relation between the charging level of the storage and the thermal energy range in which an individual appliance i in the group is operated.

When the aggregated electrical energy level of the storage is around 50 %, i.e.

$$E_{\text{el}}^{\text{total, rel}} = \frac{E_{\text{el}}^{\text{total}}}{E_{\text{el}}^{\text{total, max}}} \approx 0.5 \ , \tag{20}$$

the appliances are allowed to run their usual duty cycles comprising the whole temperature range. Note that here the switchings to maintain synchronism and those to maintain the power consumption on the setpoint are disregarded, as their impact is relatively small. If the storage level shall be higher than the mean value, "earlier than normal" switchings are triggered for appliances that are currently off. Vice versa, a lower storage level is achieved when the coordination forces appliances that are currently on to switch themselves off "earlier than normal". This relation is found to be approximately linear. As a chattering of the appliances around their lower or upper switching boundary shall be avoided, the following constraints are imposed on the total electrical energy level:

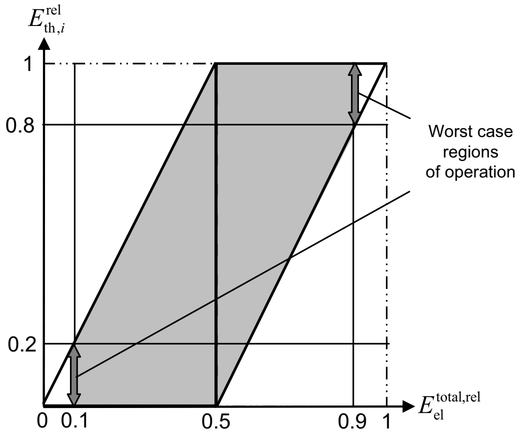

Figure 4. Impact of coordination on the duty cycle of appliance i

$$0.1 \leq E_{\text{el}}^{\text{total, rel}} \leq 0.9 \quad . \tag{21}$$

Referring again to Figure 4, this establishes worst-case operation regions for the appliances where the highest duty cycle shortening is caused. They are defined by the intervals $E_{\text{th}}^{\text{rel}} \in [0, 0.2]$ and $E_{\text{th}}^{\text{rel}} \in [0.8, 1]$, which is 20 % of the normal range. If the evolution of $E_{\text{th}}^{\text{rel}}$ is close to a straight line, the duty cycle time

$$\Delta t_{\text{cycle}} = \Delta t_{\text{dwell,ON}}^{\text{full}} + \Delta t_{\text{dwell,OFF}}^{\text{full}} \tag{22}$$

will also be shortened to 20 % in the worst case, i.e.

$$\Delta t_{\text{cycle}}^{\text{min}} = 0.2 \cdot \Delta t_{\text{cycle}}^{\text{normal}} \ . \tag{23}$$

If the appliance has a more prominently curved "first-order" (or higher order) $E_{\text{th}}^{\text{rel}}$ evolution, this is still a reasonable approximation, as the different shortening factors for the "on" and "off" phases are at least partly compensated because of the summation in equation (22). Note that normally the appliance group will be operated around a storage level of 50 % in order to keep the overall switching cost (and thus the duty cycle shortening) low.

In all cases, the quantification of the duty cycle shortening is an average property derived from the nature of the coordination algorithm. It is not necessarily an exact value for an individual appliance. However, these considerations enable an estimation of the requirements on the communication infrastructure, as the length of the appliance duty cycles has an impact on the amount of information transmitted between the different units in the coordination scheme. This will be discussed next.

B. Communication requirements

In this paper, only the in-house communication requirements will be assessed. Generally speaking, the amount of information packets that have to be transmitted between the LMH and the LMAs in a household depends on the number of appliances n_{app}, the duty cycle times of the individual appliances i denoted by $\Delta t_{\text{cycle},i}$ with $i = 1 \ldots n_{\text{app}}$, and the in-house communication step size h. The resulting estimation of an average number of information packets per time unit can be used for establishing bit rate requirements on the in-house communication. If only one packet at a time can be transmitted, the temporal distribution of the necessary information exchange has to be taken into account as well. This will not be discussed in detail here.

First, a requirement on the step size h shall be established. As the duty cycle identification task outlined in section V is done with discrete data sampled with step size h, a good representation of the input-output behavior $[u, E_{\text{th}}^{\text{rel}}]$ of the appliances by the sampled data is necessary. Especially at the switching instants t_{switch} when u changes between 0 and 1, $E_{\text{th}}^{\text{rel}}$ shall be captured with accuracy. A possible requirement can be an upper bound, e.g. $e = 10\%$, for the time span between detecting the change in $E_{\text{th}}^{\text{rel}}$ dynamics at t_{detect} instead of when it occurred at t_{switch} in relation to the dwell time of the device in the current "on" or "off" state. The shortest dwell time to be found, denoted with $\Delta t_{\text{dwell}}^{\min}$, is in this case the shorter phase ("on" or "off") of the maximally shortened duty cycle of the fastest appliance in the household. The requirement can be formulated as

$$\frac{t_{\text{detect}} - t_{\text{switch}}}{\Delta t_{\text{dwell}}^{\min}} = \frac{h}{\Delta t_{\text{dwell}}^{\min}} \leq e = 0.1 \quad . \tag{24}$$

For example, if the fastest appliance is a small refrigerator that has a normal cooling-down phase of $\Delta t_{\text{dwell,ON}}^{\text{full}} = 10$ min, the duty cycle shortening effect will reduce this in the worst case to $\Delta t_{\text{dwell}}^{\min} \approx 2$ min. Using the requirement from equation (24), the necessary step size h is determined to be $h \leq 0.1 \cdot 2$ min $=$ 12 s for being able to capture well the switching instants of the fastest device with maximally shortened duty cycle.

Having set the step size to its derived maximum, the number of appliances determine the number of packets that have to be sent from the LMAs to the LMH per time unit. The LMH has to trigger these transmissions with a single command packet (broadcast) to all appliances. The total number of packets is thus equal to

$$r_{\text{pack}}^{\text{data}} = \frac{n_{\text{app}} + 1}{h} = \frac{n_{\text{app}} + 1}{e \cdot \Delta t_{\text{dwell}}^{\min}} \quad . \tag{25}$$

Apart from that, switching impulses are sent from the LMH to the LMAs when triggered by the central coordination. Because of the requirement to prevent asynchronous switching as outlined in section VI-A, these impulses are sent to each appliance twice per duty cycle time Δt_{cycle}. Considering again the fastest appliance with the maximum duty cycle shortening, the worst-case amount of packets to be sent over time is equal to

$$r_{\text{pack}}^{\text{switch}} = \frac{n_{\text{app}}}{\Delta t_{\text{dwell}}^{\min}} \quad . \tag{26}$$

In total, an upper bound for the number of packets sent back and forth is thus described by

$$r_{\text{pack}}^{\text{total}} = \frac{\frac{1}{e} + n_{\text{app}}(1 + \frac{1}{e})}{\Delta t_{\text{dwell}}^{\min}} \quad . \tag{27}$$

Assuming that an average packet has the size s_{pack} [bit] and a packet is lost with the probability of p_{loss} in the communication channel, the worst-case average amount of data per time unit which the communication system has to handle can be described by

$$C_{\text{total}} = \frac{1}{1 - p_{\text{loss}}} \cdot \frac{\frac{1}{e} + n_{\text{app}}(1 + \frac{1}{e})}{\Delta t_{\text{dwell}}^{\min}} \cdot s_{\text{pack}} \quad . \tag{28}$$

As an example, a household with 4 appliances, the fastest of which has a minimum (shortened) dwell time of 2 min, with an error bound for the switching instant capture of $e = 10$ %, an average packet size of 120 bit and a packet loss probability of 10 % will require an in-house communication bit rate of 60 bit/s.

Note that the calculation methodology presented here only serves to clarify the order of magnitude of the required in-house bit rate. For an actual commercial implementation of the outlined load management system, a more detailed study will be required.

VII. SIMULATION RESULTS

Finally, a simulation result is presented for a household with an installed refrigerator, freezer and electric water boiler. This serves to illustrate the price calculation, the effect of enforced switchings and of user interactions. In Figure 5, the time evolution of the relevant quantities can be seen. The system is subjected to the following events: an opening of the refrigerator door for 1 minute at $t = 1$ h, a compulsory switching action of the boiler ("off" to "on") at $t = 2$ h, drawing hot water from the tap for 5 min at $t = 3$ h and a compulsory switching action of the freezer ("off" to "on") at $t = 4.5$ h. The compensation paid to the household is 1.0 ct. at $t = 2$ and 0.2 ct. at $t = 4.5$ h.

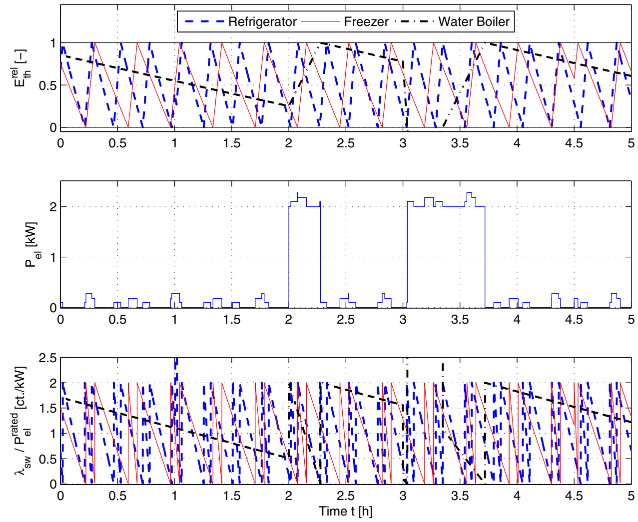

Figure 5. Simulation results for household with three appliances

VIII. CONCLUSION AND OUTLOOK

In this article, a novel approach to controlling the aggregated active power demand of a group of thermal appliances was outlined and the information exchanges between the different units in the household were clarified. A prediction and price calculation approach was shown. Evaluations of the impact of the coordination algorithm on the appliances were discussed and it was shown that the bit rate requirements for the in-house communication will be in the order of magnitude way below 1 kbit/s. Further work will be done on more elaborate local identification techniques, the modeling of other appliance types (e.g. air conditioners), the voltage dependency of the loads, and the inclusion of local generation (e.g. photovoltaics) and storages in the household energy management concept.

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