Cost Optimization of Smart Appliances

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***Abstract*--A control method of smart appliances, as part of home automation, is simulated. An optimization technique, binary integer programming, is employed to solve the scheduling of smart appliances. The cost savings achieved by interrupting the cycle of smart appliances has been explored within the optimisation suite. The home automation controller is using price signals made available by smart meters to shift and interrupt smart appliances in order to maximise the benefits for the residential consumers. Results show that the described optimisation can be used in home automation for cost savings while allowing users different levels of control on the smart appliances. A case study carried out with three smart appliances shows substantial cost savings under real time pricing.**

***Index Terms*—Home Automation; Optimal scheduling; Smart Grid; Smart Homes.**

I. INTRODUCTION

EUROPEAN Union (EU) has set three major targets to be achieved in the energy sector by 2020: reducing gas emissions by 20%, 20% increase in efficiency and 20% energy from renewable sources (RES). It is now recognized that in order to achieve these targets, new policies and technologies such as Smart Grid are essential.

It is envisioned that most of the RES energy in EU will come from wind and solar energy. Wind and solar farms operate in a different way to large scale generation technologies. The production of electricity from these generators depends on resources which are highly variable. By increasing the share of RES in the generation mix, the operation of the power system becomes difficult (or costly) and the stability of the electricity system can be endangered. Measures to mitigate this risk include increasing reserve capacities and flexible demand-side.

In this context the demand-side integration (DSI) will play an important role in the Smart Grid initiative. The European Regulator Group for Electricity and Gas has outlined in [1] some of possible benefits for implementing smart metering infrastructure in EU. It is expected that the suppliers will offer new tariffs such as time-of-use tariff (TOU) or real-time pricing (RTP) to its customers.

In [2] major energy retailers from EU have identified the benefits of adopting new tariffs as RTP for residential and commercial customers. These include: (a) a more competitive market during peak usage hours, (b) customers provide valuable reliability services to the local area, (c) reduce the frequency and magnitude of energy scarcity events, (d) avoid capacity requirements and (e) optimize the use of RES.

The residential sector in EU was responsible in 2007 for 28.8% of the consumed electricity and it is increasing with more than 2% per year. To incorporate it in the Smart Grid, demand flexibility has to be enabled with the help of DSI programs, smart meters and also smart devices. Gellings defines smart devices in [3] as devices equipped with advanced control and communication capabilities. Such device should accept external signals, for instance RTP, user settings and outside temperature and adjust their operation in response to the received signals.

In this paper a control method for home automation that schedules the operation of smart appliances is proposed. The home automation controller receives RTP tariff from the supplier through the smart meter installed in the household. The home automation controller employs cost optimization to maximize the savings on consumed energy by shifting domestic loads. The smart appliances considered in this study are: washing machines, dish washers, and tumble dryers. The smart behavior of these appliances is modeled including features such as delaying the start time and cycle interruptions. Binary integer programming was used to perform the optimization.

II. BACKGROUND

An extensive study of the potential benefits of new devices such as smart appliances has been completed in the Smart-A Project [4]. This project focused on assessing features of smart appliances that allow them to adapt their operation to variation in energy supply. In the study, the ability of smart appliances to perform two types of load shifting operations, smart timing and interruptions of appliance cycle, was reviewed. The results show a potential benefit for adopting smart appliances of over €50/year for each kW of controllable load in many countries in Europe by avoiding fuel cost in fossil peak power plants.

Smarthouse/SmartGrid is a European project that is investigating different ICT architectures for houses that will facilitate them to interact in an envisioned Smart Grid. In the second field test of this project [5] the automated response to price signals is investigated. One hundred houses in the city of Manheim in Germany have been fitted with a home automation system. The owners were offered day-ahead variable electricity tariffs as an incentive to shift different loads. The system can automatically schedule appliances (washing machines, dish washers, etc) to operate in periods

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with low energy prices. Results from the trial are expected by the end of 2011.

By optimizing the schedule of an immersion heated hot water tank, reference [6] shows that the use of price-based incentives can promote wind generated electricity. RTP tariffs have been used in [7] to simulate a home energy management system which shifts the controllable residential loads to low price periods. The optimal schedule results from linear programming. Findings of this study confirm that using home automation can reduce the household electricity bill and also the peak-to-average ratio in load profile.

III. Implementation

A. Appliance Model

A household with smart domestic appliances was considered. The typical power demand profiles for different domestic appliances are given in the Smart-A project [4]. The load profile can be broken down in a number of processes with approximately constant power levels as shown in Fig.1. The operation of the appliance could accept delays between processes (at processes boundaries) without compromising the service quality of the appliance. One advantage of this method is the high level of control that can be imposed on the appliance. The parameter $T_{off\,p}$ which represents the maximum interruption time between a process p and the next process was introduced. $T_{off\,p}$ depends on the thermal loss that occurs during the appliance interruption. In this study it was assumed that a maximum interruption of one hour is possible.

As an example in Fig. 1 the power demand profile of a washing machine is shown. This has seven processes with constant power demand. Thus it was assumed that the washing machine is composed of seven virtual appliances (processes), each operating for a quarter of hour.

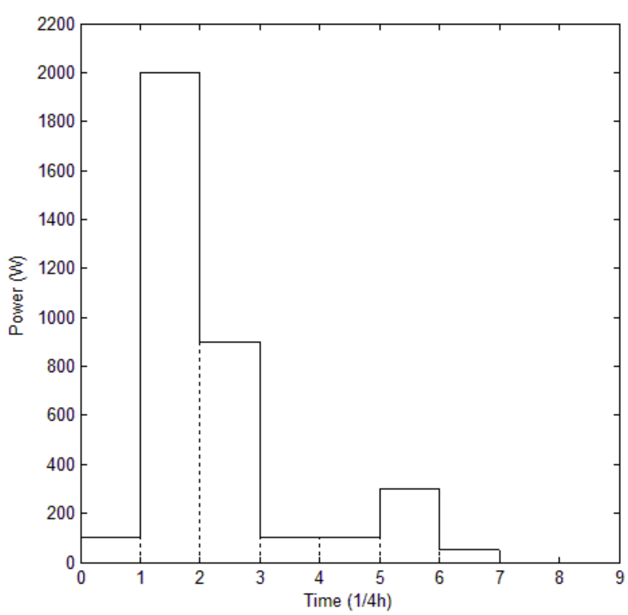

Fig. 1. Load profile for washing machine

The assumed time step is fifteen minutes. For each virtual appliance (process) a binary operation vector was defined:

$$X_v = [x_v^1,\ x_v^2, \dots, x_v^h, \dots, x_v^H,] \qquad (1)$$

Where v represents the virtual appliance index, h the quarter-hourly time interval index and H corresponds to the number of quarter-hourly time intervals throughout a time window. The virtual appliance is *'on'* for the duration of the time interval h if $x_v^h = 1$and is *'off'* for the same interval if $x_v^h = 0$. The virtual appliance has a constant power demand P_v within a time interval h.

For the correct operation of the smart appliances, the order of the virtual appliances was kept as in the original load profile. Therefore if one virtual appliance v is supplied ($x_v^{h_1} = 1$) at a time h_1, the next virtual appliance of the same appliance has to be supplied ($x_{v+1}^{h_2} = 1$) at a time $h_2 > h_1$.

The end-user comfort is an important factor in the implementation of Smart Grid technology [9]. A user may not want to run an appliance which produces excessive noise when it operates after 10pm. Therefore a user can set the time t_e at which the appliance should have already finished its cycle. The user has the possibility to set a starting time t_s, that represents the earliest time for the appliance to start. The virtual appliances have to run in the time interval defined by t_s and t_e.

$$\sum_{h=t_s}^{t_e} x_v^h = 1 \qquad \forall v \in V_a \qquad (2)$$

Where V_a is the set of virtual appliances that make up the load profile of appliance a. The difference between the time interval $[t_s; t_e]$ and the length of the appliance cycle represents how much time the user offers for the smart appliance to be scheduled, or a measure of the user complaisance with the home automation. This parameter will be named user defined timeframe. Increasing its value will result in a larger timeframe for the appliance to optimize its operation.

B. Cost function

With the implementation of smart metering systems it is possible to offer innovative tariffs such as RTP tariff structures. RTP tariffs can be transmitted to customers in a time range between seconds to days ahead. In this study the RTP tariff used is based on the RTP scheme implemented by Ameren Illinois Power Co. for residential customers [10]. The price of electricity varies hourly and the customers are notified of the hourly prices on a day ahead basis. It is assumed that the tariff is broadcast to customers with the help of the smart metering communication infrastructure and from the smart meter to the home automation controller. Based on the RTP tariff, a price vector given by (3) is considered.

$$C = [c^1,\ c^2, \dots, c^h, \dots, c^H] \qquad (3)$$

The total cost of energy consumed by the appliances, as denoted by g in (4), is the cost of energy consumed by all the virtual appliances:

$$g = \sum_{v \in V} \sum_{h=1}^{H} c^h x_v^h P_v \Delta t \qquad (4)$$

Where V is the virtual appliances set that constitute the residential consumer demand. P_v is the power level of the virtual appliance (process) and Δt is equal to the quarter hour time interval.

C. Optimization Model

The objective of the optimization scheme is to schedule the appliances in order to minimize the cost of the consumed energy during a time period. The objective function (5) of the optimization is the cost function from (4). The decision variables of the optimization are the virtual appliances binary vectors.

$$\min_{X_v} \left\{ \sum_{v \in V} \sum_{h=1}^{H} c^h x_v^h P_v \Delta t \right\} \qquad (5)$$

The optimization model has two inequality constraints applicable on the decision variables. The first of these constraints states that virtual appliances have to be supplied in the same order as the original load profile. The equation form of this constraint is given in (6).

$$\left(\sum_{h=1}^{H} x_{v+1}^h h - \sum_{h=1}^{H} x_v^h h \right) \geq 1 \qquad \forall v \in V_a \qquad (6)$$

The second inequality constraint on the binary vectors is linked to the interruption time $T_{off\,v}$ between virtual appliances. The value of $T_{off\,v}$ can differ for each appliance, and between processes of the same appliance. The constraint on the binary operation vectors is written in (7). Using (7) any interruption restrictions between two processes can be modelled.

$$\left(\sum_{h=1}^{H} x_{v+1}^h h - \sum_{h=1}^{H} x_v^h h \right) \leq T_{offv} \qquad \forall v \in V_a \qquad (7)$$

The optimization includes an equality constraint that facilitates the implementation of user preferences in the model. The constraint is expressed by equation (2).

Binary integer programming is applied to solve the optimization problem.

IV. Test results

In this stage of the study the appliances that will be controlled are: washing machine, tumble dryer and dish washer. According to the survey [11] these appliances are viewed by end-users as appliances that contribute mostly to the electricity bills. Thus the users are likely to accept and cooperate with home automation that will control these three appliances to lower the electricity bill. The load profiles for each of the three smart appliances are given in Table 1. P_1 to P_8 are the power levels of the virtual appliances, as described in section III. The washing machine has seven independent processes or virtual appliances, the dishwasher has eight and the tumble dryer has six.

Table 1. Data input for optimization

Power Level	Load 1 (Washing Machine)		Load 2 (Dish Washer)		Load 3 (Tumble dryer)	
	Start time	02:45	Start time	14:30	Start time	00:00
	End time	06:30	End time	18:45	End time	24:00
	$T_{off\,1,6}$	0 min	$T_{off\,1,7}$	60 min	$T_{off\,1,5}$	0 min
P_1	100 W		80 W		2000 W	
P_2	2000 W		2000 W		2000 W	
P_3	900 W		80 W		2000 W	
P_4	100 W		80 W		1600 W	
P_5	100 W		80 W		1300 W	
P_6	300 W		2000 W		940 W	
P_7	50 W		300 W		-	
P_8	-		150 W		-	

An example of scheduling of appliances using cost optimization is shown in Fig 2. The time window of the optimization is 24 hours. RTP tariff is used as stimulus for the optimizer to shift loads. Each virtual appliance has a corresponding binary vector in the optimization model which is used as decision variable. In total there are 21 binary operation vectors which are used as decision variables in the optimization model.

The simulation employs different values for user settings (t_s and t_e) and for the maximum interruption durations ($T_{off\,v}$). These parameters are given in Table 1. The results will demonstrate how the optimization model reacts to different values of input parameters.

For the first appliance, represented in Fig. 2 as load 1, the user has set the operational interval $[t_{s_1};\ t_{e_1}]$. This appliance does not permit interruptions as $T_{off\ v}$=0 for all of the constituent virtual appliances. Therefore, in Fig. 2 it can be observed that the appliance cannot be interrupted to avoid the peak price period between 4:00 and 5:00. The second appliance permits interruptions and it can be seen that it stops at 16:00 and starts again at 17:00, avoiding the extra charge from peak electricity price. For the third appliance the user sets the operational interval for the appliance to maximum (00:00 – 24:00), therefore the appliance was scheduled for the time interval where it will achieve the lowest electricity charge.

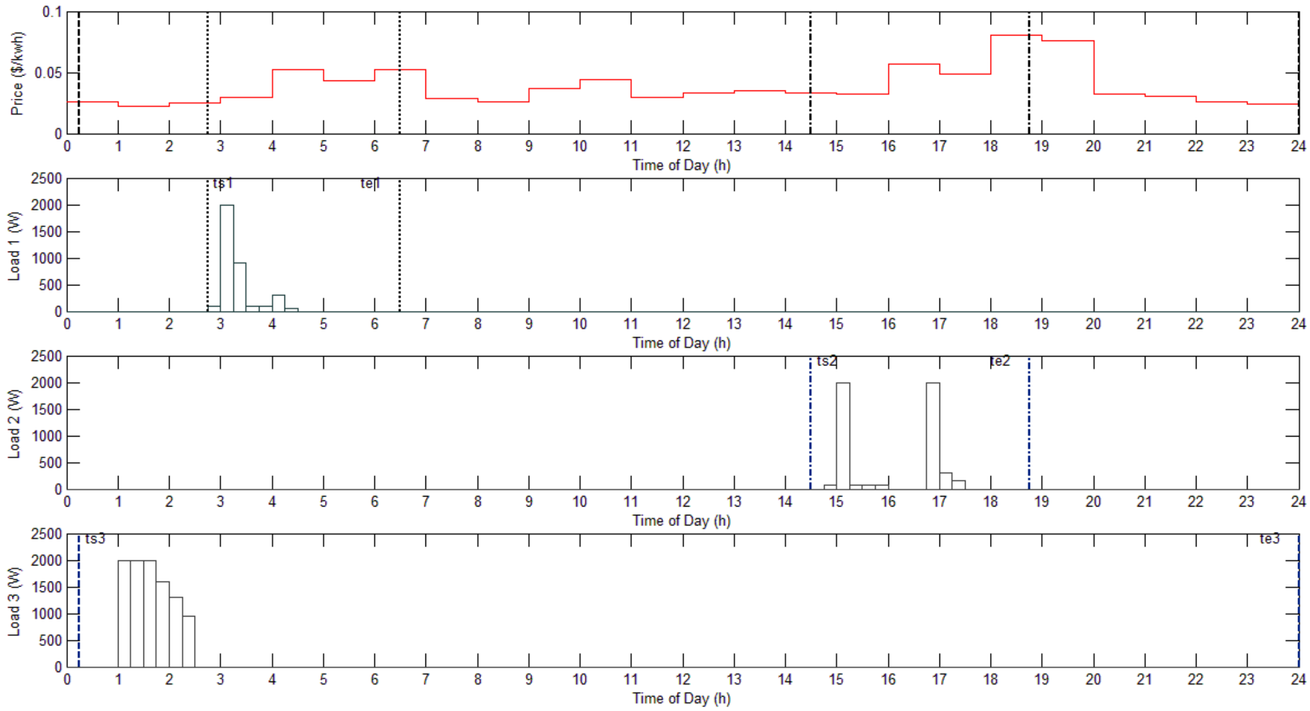

Fig. 2. Schedule of smart appliances using binary cost optimization under RTP tariff

Further, the cost optimization of smart appliances has been implemented for a household under the RTP tariff. The house demand profile has been obtained from the CREST high resolution model of domestic electricity use [12]. Two scenarios have been investigated: a winter week and summer week. The simulation assumes that the household has three residents and is equipped with the smart appliances described and additional non-controllable appliances. The set of non-controllable appliances and their operating times are different in the two cases.

In the first scenario the cost savings after cost optimization can be observed in Fig. 3 as a function of the user defined timeframe for the operation of appliances. Cost savings are a result of shifting the appliances operations from typical time of use to optimal schedule. The cost savings for four cases have been investigated, where the maximum interruption($T_{off\,v}$) allowed by the appliances is: 0, 15, 30 and 60 minutes. The cost savings increase steeply with the user timeframe for the first five hours and at a slower pace from that point. Maximum cost savings of more than 18 % from the electricity bill can be reached with more than seven hours flexibility.

The maximum interruption duration that the appliances allow has a significant contribution to savings only for the first hour. This result can be explained if we look at the price average of the winter days in Fig. 5 from the appendix. Savings made with the interruption feature of the appliances are resulted by avoiding price peaks. The winter hourly tariff offers only two price peaks (at 10:00 and 18:00). For a user timeframe value greater than two hours the smart appliance operation will be shifted from the peak price period towards a non-peak period where the interruption feature cannot be exploited.

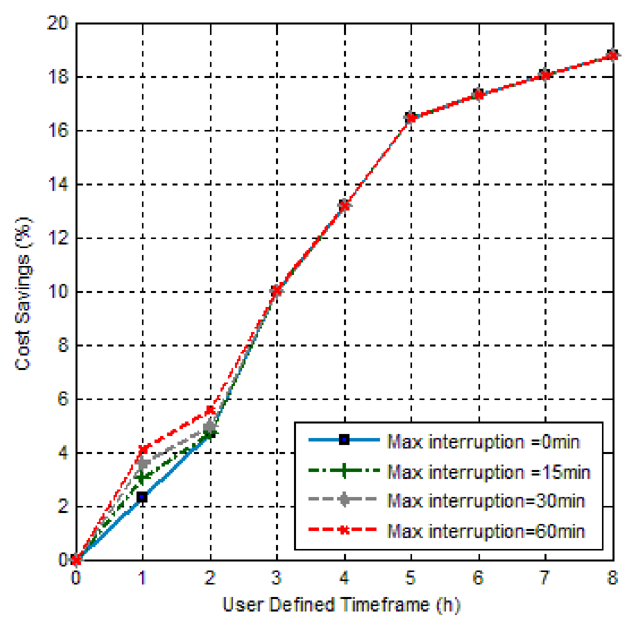

Fig. 3. Cost savings on electricity bill for a house equipped with smart appliances in a winter week

The optimization results for the summer week scenario are presented in Fig. 4. In this scenario the cost savings for the same four values of $T_{off\,v}$, as in the first scenario (0, 15, 30 and 60 minutes), have also been analyzed. The cost savings for the summer case can reach 16% when the user timeframe for the appliance operation is greater than 7 hours.

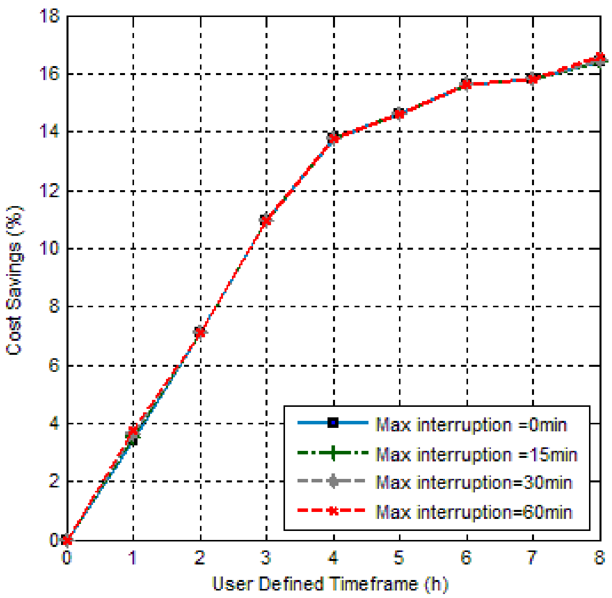

Fig. 4. Cost savings on electricity bill for a house equipped with smart appliances in a summer week

As in the first scenario the interruption duration parameter has a small impact on cost savings compared with the savings from the user defined timeframe parameter. The price average for the summer represented in Fig. 5 shows a single price peak at 17:00 where the smart appliances can be interrupted to save cost. Having a user timeframe greater than one hour will allow the operation of the smart appliance to be shifted towards a non-peak price period. In these time intervals the smart appliance interruption feature cannot offer further benefits.

V. Conclusions

In this paper a method of controlling smart domestic appliances is presented. The controller takes advantage of new technologies such as smart metering and home automation together with services such as RTP tariff to minimize the cost of running smart appliances. The method employs optimization with a cost function as objective. The smart appliance features such as smart timing and cycle interruption are implemented in the optimization. The optimization problem is solved using binary integer programming. The test results show that, using our optimization, the smart appliances can be controlled in order to minimize the operation cost. As the user allows more time for the automatic operation of appliances, it can be observed that the cost savings start saturating. Increasing the interruption duration of smart appliances cycles has a small influence on the cost savings with the RTP tariff employed in this study. It can be concluded that a more granular RTP tariff (e.g. half hourly) that includes more price peaks has to be used to utilize the full potential of the smart appliances interruption feature.

VI. Acknowledgments

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VII. References

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VIII. Appendix

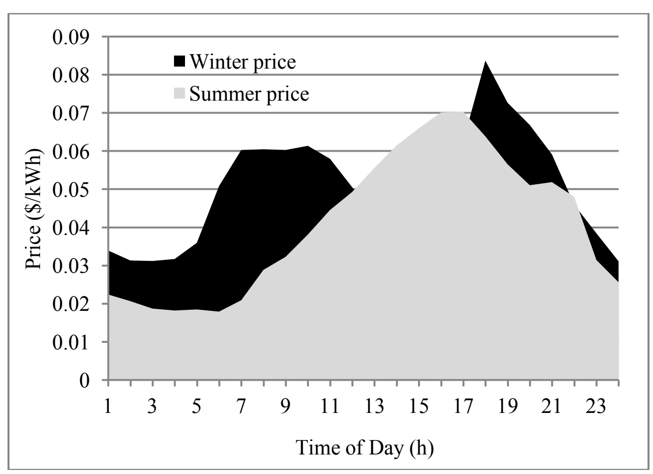

Fig. 5. Averaged prices over one week in winter and summer