A HOME APPLIANCE CONTROL SYSTEM FOR ENERGY MANAGEMENT

Hanife APAYDIN ÖZKAN[*]

Eskisehir Technical University, Department of Electrical and Electronics Engineering, Eskisehir, Turkey

Keywords	Abstract
Home Energy Management, Home Appliance, Electricity Cost, Peak Demand, Algorithm.	In this work, a Home Appliance Control System is proposed as a Home Energy Management System for preventing high peak demand and reducing electricity cost while keeping user comfort. The proposed Home Appliance Control System consists of a home equipped with smart appliances, grid, communication network and a Main Controller and it is based on appliance interference under certain conditions. Appliances are separated as controllable, semi-controllable and uncontrollable according to their effects on user comfort. Main Controller is not allowed to interfere with uncontrollable appliances, but with semi-controllable and controllable appliances as much as it is permitted. Appliance interference is done on real time in the order of appliance priority defined by the user due to expected power consumption and the grid limit. The corresponding control algorithm of Home Appliance Control System is also developed. Simulation results demonstrate the effectiveness of the proposed system on achieving the intended goals.

EV ENERJİ YÖNETİMİ İÇİN EV CİHAZLARININ KONTROLÜ

Anahtar Kelimeler	Öz
Ev Enerji Yönetimi, Ev Cihazları, Elektrik Maliyeti, Yüksek Talep, Algoritma.	Bu çalışmada kullanıcı konforunu korurken elektrik maliyetini düşürmeyi ve anlık yüksek güç talebini önlemeyi hedefleyen bir Ev Enerji Yönetim sistemi olarak, bir Ev Cihazları Kontrol sistemi önerilmiştir. Önerilen Ev Cihazları Kontrol sistemi akıllı cihazlar, şebeke, haberleşme ünitesi ve bir ana kontrolcüden oluşmakta; ve cihazlara belirli koşullar altında müdahale etme esasına dayanmaktadır. Cihazlar kullanıcı konforuna etkilerine göre kontrol edilebilir, yarı-kontrol edilebilir ve kontrol edilemez olarak üçe ayrılmaktadır. Ana kontrolcünün kontrol edilemeyen cihazlara müdahale etmesine izin verilmezken, yarı kontrol edilebilir ve kontrol edilebilir cihazlara izin verilen ölçüde müdahale etmesine izin verilmektedir. Cihazlara kullanıcı tarafından belirlenen öncelik sırası ve belirlenen şebeke limitleri dikkate alınarak gerçek zamanlı müdahale edilmektedir. Önerilen Ev Cihazları Kontrol sistemine uygun kontrol algoritması da geliştirilmiştir. Simulasyon sonuçları sistemin amaçlanan sonuçlara ulaşmadaki başarısını göstermektedir.

1. Introduction

Due to the economic development, increase in global population, and widespread use of technological devices, there has been rapid rise in energy demand recently. Therefore, efficient use of existing energy is a big challenge nowadays. The energy consumed in the houses constitutes a significant part of the total energy demand (Rahimi & Ipakchi, 2010). Hence, for appropriate management of home energy consumption, Home Energy Management Systems (HEMS) have been proposed, recently.

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[*]Corresponding author: hapaydin1@eskisehir.edu.tr, +90-222-335-0580/6468

Beside the increase in total energy demand, high peak demand, which causes overload and costly malfunctions in the network-putting traders in trouble, emerges as a matter to be considered. The user side contribution to the solution of high peak demand is provided by HEMS, while energy trader side contribution is realized by applying different electricity pricing such as real-time pricing, critical peak pricing and time-of-use (TOU) pricing (Du & Lu, 2011). In this work, TOU pricing which charges higher rates at peak demand periods and lower rates at off-peak demand periods is considered. By this pricing policy, users are encouraged to use appliances at times when the price is cheaper. Besides, HEMSs consider efficient use of energy at homes for providing sustainability of environment, user comfort and lower electricity cost for user as well as lower breakdown and maintenance costs for energy traders.

There are several papers on HEMS with different aims in the literature. Through the numerous works aiming at reducing electricity cost, stochastic dynamic programming with future price uncertainty is proposed to schedule the power consumption in (Kim&Poor,2010), while a dynamic load priority method is proposed to change the load priority during a demand response event in (Fernandes at al. 2014). Authors of (Conejo at all, 2010) proposed a simple linear programming based appliance control algorithm, while appliance scheduling is considered by using linear approaches in (Schweppe at al., 1989; Daryanian & Bohn, 1989).

In some other studies on HEMS, avoiding high peak demand as well as reducing electricity cost is considered: An automation system (Chauhan & Chauhan, 2019) is proposed to switch ON/OFF the appliances according to requirement as well as according to price. In (Mohsenian-Rad at al. (2010)), authors consider not only the energy cost minimization problem but also the problem of minimizing the peak-average ratio in the total load. They use a game theoretic approach to schedule energy consumption. A collaborative scheduling with genetic algorithms is proposed to reduce the electricity charges of a smart building by by reducing the electricity usage at peak time in (Lee & Bahn (2013)) while in (O'Neill at al. (2010)) Q-learning approach is presented to learn a residence's behaviour and automatically make optimal energy scheduling and allocation decisions. To reduce the peak demand, a consensual negotiation-based decision model is presented in (Bui at al. (2018)) using appliances with IoT concept and appliance prioritization approach are used in (Pipattanasomporn at al., 2012). The performance of an in-home energy management application has been evaluated in (Kantarci & Mouftah, 2011). On the other hand, a small number of works on HEMS consider user comfort as well as reducing electricity cost and avoiding high peak demand (Apaydin-Ozkan, 2016; Izmitligil & Apaydin-Ozkan, 2018). Although user comfort was also taken into consideration besides reducing the electricity cost and avoiding the high peak demand in these works, allowing comprehensive interference with some appliances and ignoring user preferences kept the user comfort consideration at a limited level.

In this work, a Home Appliance Control System (HACS) is proposed as a HEM for preventing high peak demand and keeping user comfort while reducing the electricity cost. The proposed HACS consists of a home equipped with smart appliances, grid, communication network and a Main Controller (MC) and it is based on appliance interference under certain conditions. Appliances are separated as controllable, semi-controllable and uncontrollable according to their effects on user comfort. MC is not allowed to interfere with uncontrollable appliances, but with semi-controllable and controllable appliances as much as it is permitted. Appliance interference is done on real time due to expected power consumption and the grid limit in the order of appliance priority defined by the user according to his preferences. The corresponding control algorithm of HACS is also developed and implemented.

In this study, unlike most studies in the literature, simultaneous consideration of keeping user comfort, avoiding high peak demand and reducing the electricity cost is provided. Besides, real power consumption profiles of appliances are used instead of their average powers assuring to detect even short-term high peak demands. Simulation results demonstrate the effectiveness of HACS on achieving the intended goals.

2. Home Appliance Control System

Home Appliance Control System (HACS) intends to reduce electricity cost and prevent high peak demand by keeping user comfort. In HACS, the home consists of smart appliances (e.g., air conditioner, washing machine, dishwasher, refrigerator, TV and lamps), grid, communication unit and a Main Controller (MC).   The schematic diagram of HACS is given in Figure 1.

MC is the brain of the HACS, which communicates and controls appliances according to the developed control algorithm via communication units. In the system, one execution period (e.g., one day, 24 h) is discretized into a prescribed number T of uniform time slots, i.e., $T = t \in \{1, 2, ..., T\}$, so that the total number of time slots in a day is $T = 24/\Delta_t$.
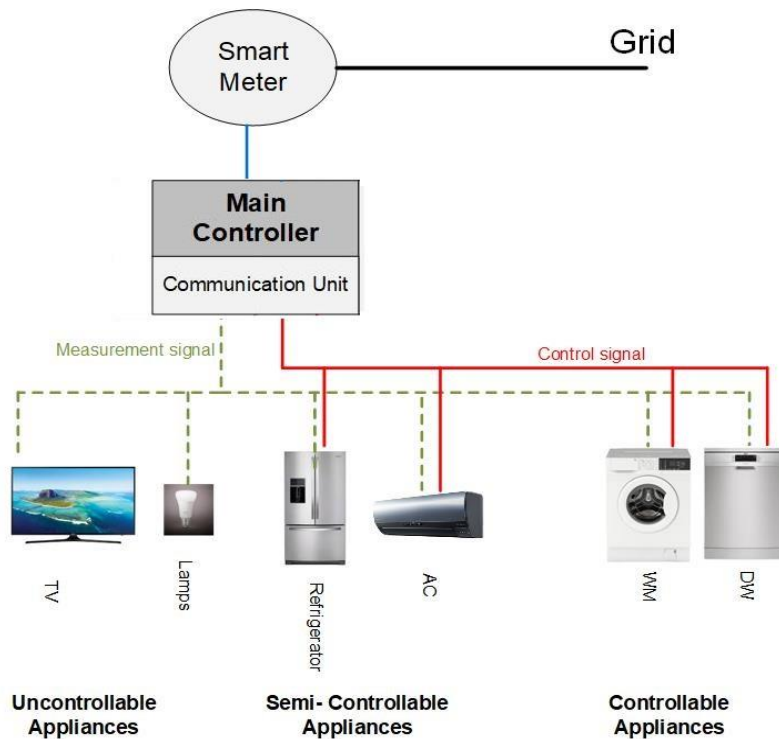
Figure 1: The schematic diagram of HACS

2.1 Home Appliance Control Algorithm

In HACS, appliances are separated as controllable, semi-controllable and uncontrollable. The set of these appliances is represented by L, i.e., $L = L_{UC} \cup L_{SC} \cup L_C$, where L_{UC} is the set of uncontrollable appliances, L_{SC} is the set of semi-controllable appliances while L_C is the set of controllable appliances. Status of appliances consists of working modes; such as, on-standby-off and different program modes; such as, normal, economic etc.

Appliances whose status is directly depends on user preferences, i.e., TV and lamps, are called as uncontrollable appliances. In order not to deteriorate user comfort, MC cannot interfere with the status (working modes and program modes) uncontrollable appliances. Power consumption profiles of uncontrollable appliances is illustrated via the real power consumption profile of a TV in Figure 2.
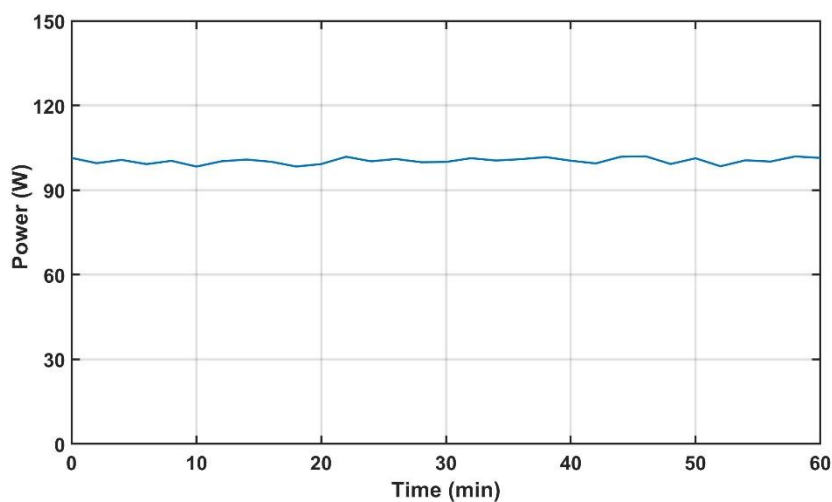

Figure 2: Power consumption profile of a TV

Appliances, whose working modes directly depends on user preferences, (i.e., air conditioner, refrigerator and water heater etc.) are called as semi-controllable appliances. In order not to deteriorate user comfort MC cannot interfere with working modes of semi-controllable appliances but can interfere with their program modes by changing their current program mode to the economic one. Power consumption profiles of semi-controllable

appliances is illustrated via real power consumption profile of normal and economic program modes of a refrigerator in Figure 3.
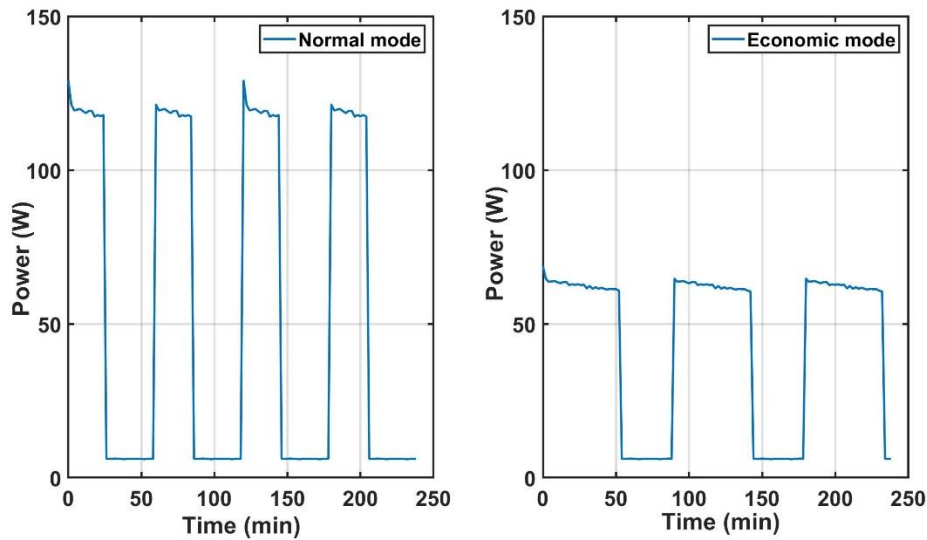

Figure 3: Power consumption profile of a refrigerator (Normal and Economic mode)

Appliances whose program modes directly depends on user preferences (e.g., washing machine, dishwasher) are called as controllable appliances. These appliances have different program modes (i.e., 'regular', 'long', 'express', and 'special') according to the amount, dirtiness and type of the stuff in themselves. Power consumption profiles of controllable appliances is illustrated via real power of a dishwasher in Figure 4.

When user wants to operate a controllable appliance $a \in L_C$ in a day, he defines an operation time interval $\begin{bmatrix} t_s^a & t_f^a \end{bmatrix}$ where t_s^a specifies earliest time of starting and t_f^a specifies the latest finishing time of the operation of a. In order not to deteriorate user comfort MC cannot interfere with the program modes of controllable appliances, but can interfere with their working modes by postponing the starting time under the condition that appliance operation terminates before the latest finishing time. That is, if the present time $t \in T=$ is in the operation time interval of $a \in L_C$, thus $t \in \begin{bmatrix} t_s^a & t_f^a \end{bmatrix}$, MC can interfere if and only if $t - t_f^a \geq \Delta^a$, where Δ^a is the operation duration of a.
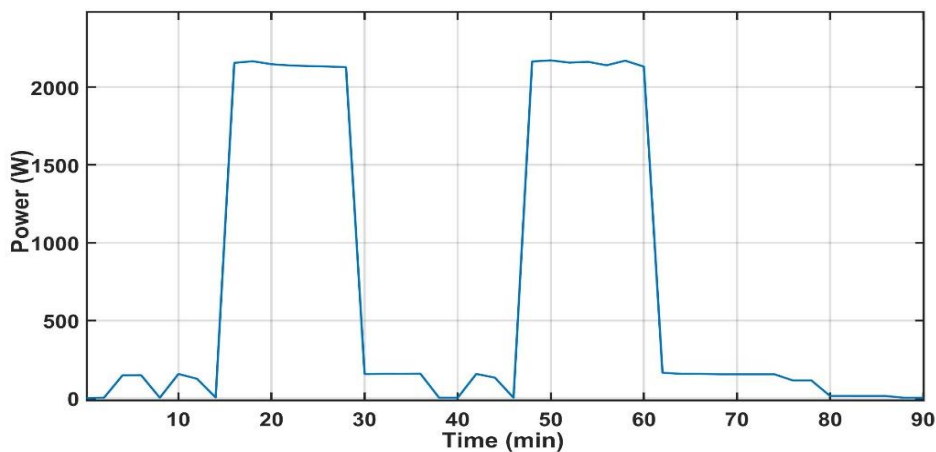

Figure 4: Power consumption profile of a dishwasher

2.2 Home Appliance Control Algorithm

HACS aims to prevent high peak demand and reducing the electricity cost while keeping user comfort. In HACS, in order to reduce electricity costs and prevent high peak demand on grid, time varying limit on power that can be drawn from the grid, namely grid limit, i.e., $P_{\lim}^{grid}$, is specified and stated in the contract between the resident and the energy trader. This grid limit shifts electricity consumption which is high during peak demand periods (such as, evenings when all occupants are at home) to off peak hours leading electricity cost reduction as well as avoiding high peak demand.

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HACS is based on appliance interference in the operation of appliances. Interference decision is made according to the expected power consumption and the grid limit. Expected power consumption of a residence at any time slot $t \in T =$, i.e., $P_{\exp}(t)$, is the sum of expected power consumptions of all appliances. Expected power consumption of an appliance is obtained from the power profile vector, which is previously created in database by measuring average power consumption of that appliance. At the beginning of each time slot $t \in T =$, MC communicates with the appliances, and receives the current status request and calculates corresponding expected power consumption at that time slot, i.e., $P_{\exp}(t)$ due to the following approach:

- If the expected power consumption does not exceed the grid limit at that time slot t :, i.e., $P_{\exp}(t) \prec P_{\lim}^{grid}(t)$:

  MC allows all appliances to work as their request at that time slot.

- If the expected power consumption exceeds the grid limit at that time slot t :, i.e., $P_{\exp}(t) \geq P_{\lim}^{grid}(t)$:

Appliance interference is done on real time due to grid limit and the expected power consumption in the order of appliance priority defined by the user. MC interferes with the appliances in the order of appliance priority (includes only controllable and semi-controllable appliances) defined by the user according to his preferences for considering user comfort. Note that, MC is allowed to interfere with semi-controllable appliances via shifting their operation and controllable appliances via switching their operation mode. MC calculates the new expected power consumption in the case that it interferes with the first appliance in the priority order. If grid limit is not exceeded at that time slot t :after this interference, interference is realized and no more interference is made. Updated status is settled and sent to local controllers of appliances as allowed status. If grid limit is still exceeded, MC calculates the new expected power consumption in the case it interferes with the next appliance in the priority order and so on. The corresponding control algorithm of HACS procedure is developed and given as a flowchart in Figure 5.
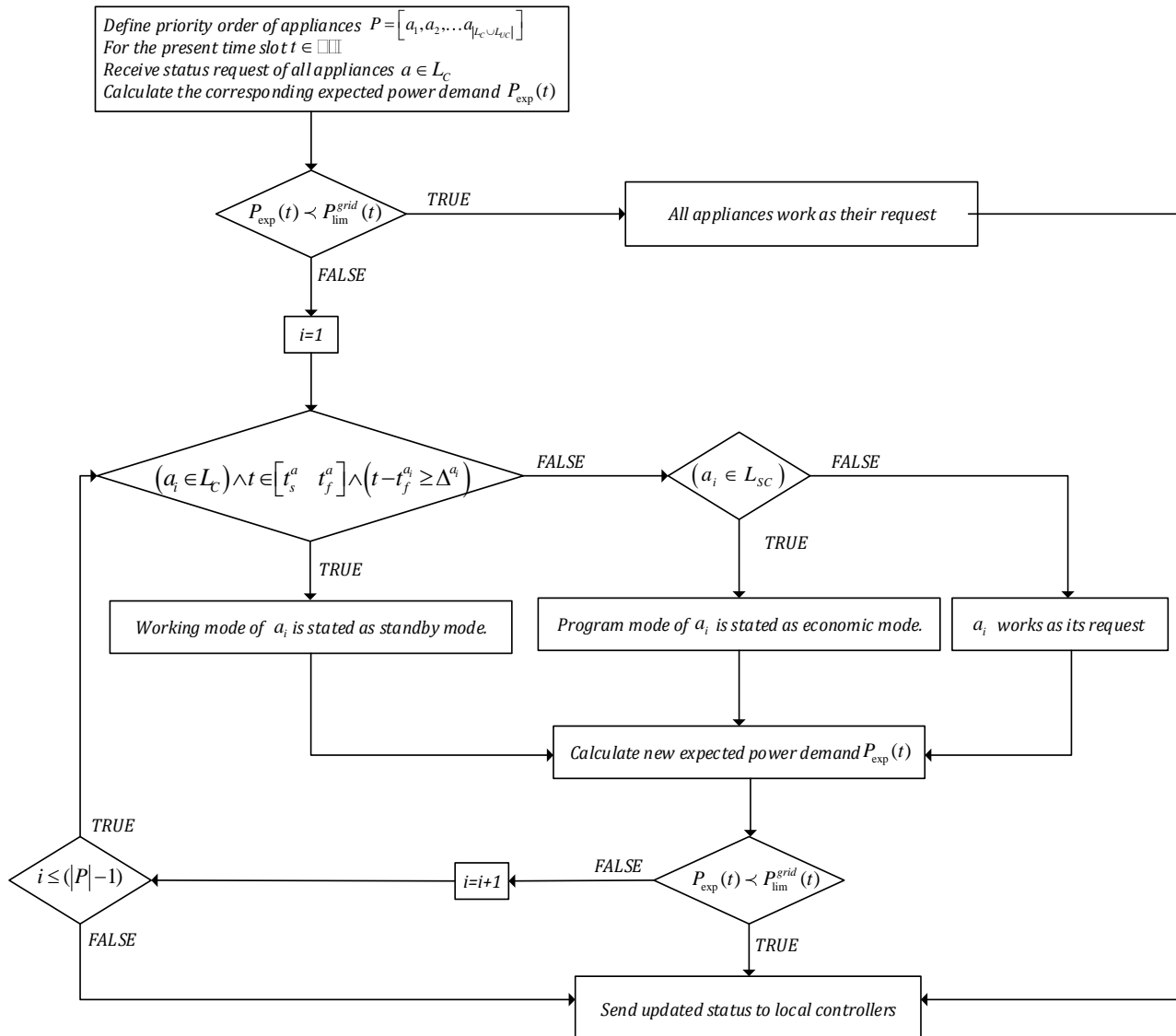

Figure 5: Flowchart of HACS control algorithm

3. Case Study

In order to present the effects of HACS on reducing electricity cost and preventing high peak demand while keeping user comfort, several scenarios are created and analyzed. In the created scenarios, a home equipped with $L_C =$ {Washing Machine (WM), Dish Washer (DW)}, $L_{SC} =$ {Air Conditioner (AC), Refrigerator (Ref) }, $L_{SC} =$ {TV, Lamps} is considered. Each semi-controllable appliance assumed to have economic program mode as well as other ones such as normal, special, speedy etc. Operation durations of controllable appliances is assumed as 90 min., thus $\Delta^{WM} = \Delta^{DW} = 90\,min$. Power profile vectors of all appliances are generated in the historical database by measuring their power consumptions using Yokogawa WT 210 power analyzer. For grid power, TOU periods and prices set by Turkish Electricity Distributor Company (TEDAS) are used (as provided in Table 1) and the grid limit, i.e. P_{lim}^{grid} is chosen constant throughout the day. In the scenarios, time slot duration is taken as 2 min., thus $\Delta_t = 2$.

Table 1: TOU Rates

Duration	Cost(Euro/kWh)	P_{lim}^{grid}
6:00 - 17:00	0.094	3000 W
17:00 -22:00	0.136	3000 W
22:00 -6:00	0.059	3000 W

In this section, two scenarios will be presented in details. For the first scenario that will be presented here, priority order is defined as P=[DW, WM, AC, Ref] by the user. Besides, the user sets WM to run in [21:10 23:59], and DW to run in [20:00 23:00]. Refrigerator works throughout the day, AC works in [06:00 8:30] and [16:00 23:59], TV works in [20:00 23:59] and lamps work in [17:30 23:59].

For the uncontrolled case, the total power consumption evaluation of the home is given in Figure 6. For this case WM and DW start working at their earliest starting times ($t_s^{WM} =$21:10, $t_s^{DW} = 20:00$) , while all other appliances work at the user-adjusted program modes. As it is clear from the graph, high peak demand occurs at 20:16 – 20:30 and 21:14 -21:26. The maximum demand is 4306.48 W while the electricity cost of the day is 1,61 Euro.

For this scenario, MC directs the appliances according to HACS as follows: Starting time of WM starts working at 21:46 after 36 min from its earliest starting time; while DW starts working at 21:20 after 80 min from its earliest starting time. Air-conditioner works during [21:00 21:20], while 20 min of it proceeds in economic mode. The total power consumption evaluation of the home for this controlled case is given in Figure 7. HACS completely avoids all peak demands exceeding the specified grid limit by reducing the peak demand levels by approximately 37.41%. The maximum demand is occurred as 2695.40 W. The electricity cost of the day is 1.56 Euro, which is 3.10% less than the uncontrolled case.
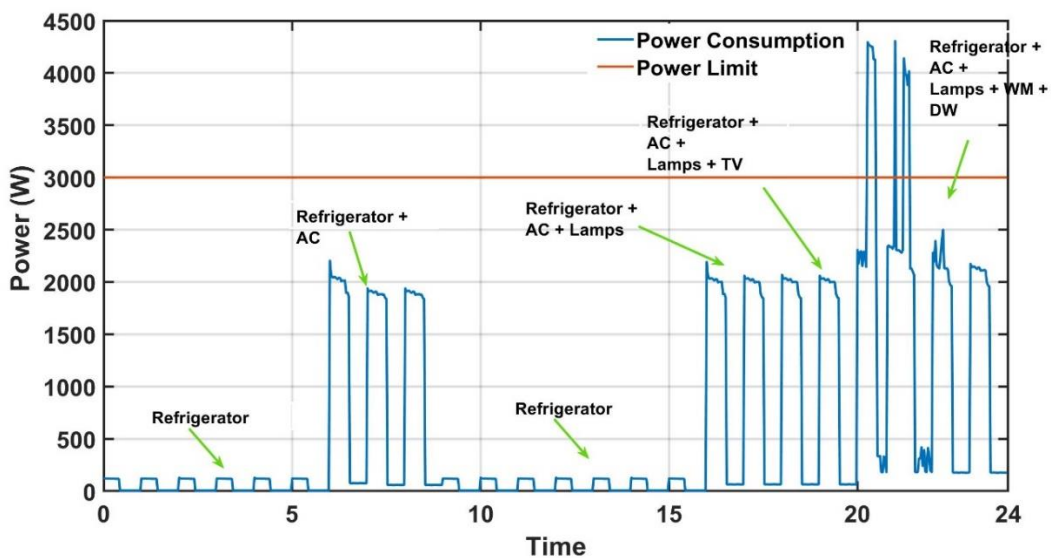
Figure 6: Evaluation of total power consumption for uncontrolled case – Scenario 1
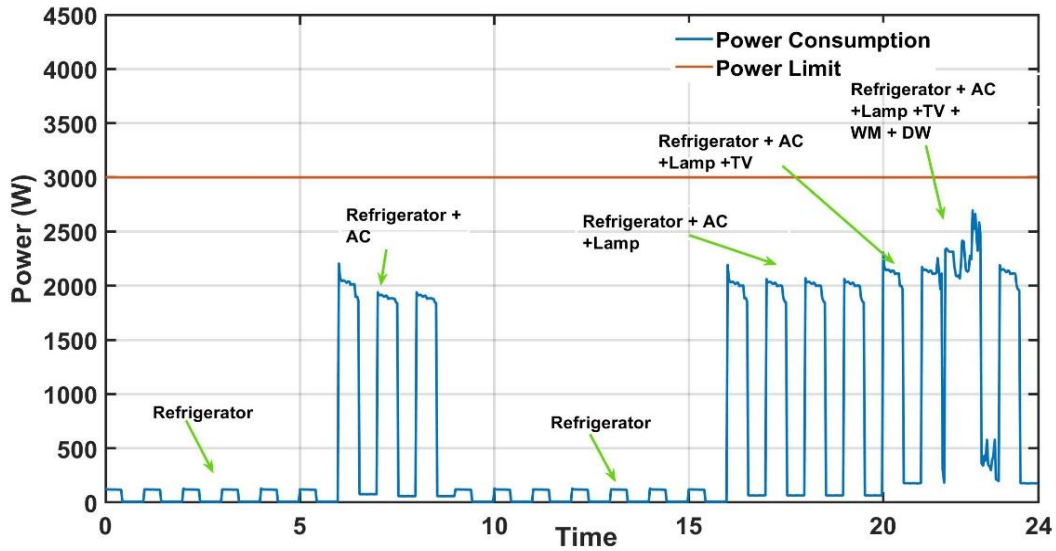
Figure 7: Evaluation of total power consumption for controlled case - Scenario 1

For the second scenario that will be presented here, the priority order is defined as P=[WM, DW, AC, Ref] by the user. Besides, the user sets WM to run in [14:00 20:00], and DW to run in [20:30 23:00]. Refrigerator works throughout the day, AC works in [06:00 8:30] and [18:00 23:59], TV works in [21:00 23:59] and lamps work in [18:00 23:59].

For the uncontrolled case, the total power consumption evaluation of the home is given in Figure 8. For this case WM and DW start working at their earliest starting times (t_s^{WM} =14:00, t_s^{DW} = 21:30), while all other appliances work at the user-adjusted program modes. As it is clear from the graph, high peak demand occurs at 22:24– 22:30. The maximum demand is 4286.89 W while the electricity cost of the day is 1.34 Euro.

For this scenario, MC directs the appliances according to HACS as follows: Starting time of WM starts working at 14:00 without any delay; while DW starts working at 22:02 after 32 min from its earliest starting time. Air-conditioner works during [22:18 22:34], while 16 min of it proceeds in economic mode. The total power consumption evaluation of the home for this controlled case is given in Figure 9 while no peak demand occurs. The maximum demand is occurred as 2462.20 W and it is 42.56 % less than the uncontrolled case. The electricity cost of the day is 1.22 Euro, which is 9.06 % less than the uncontrolled case.
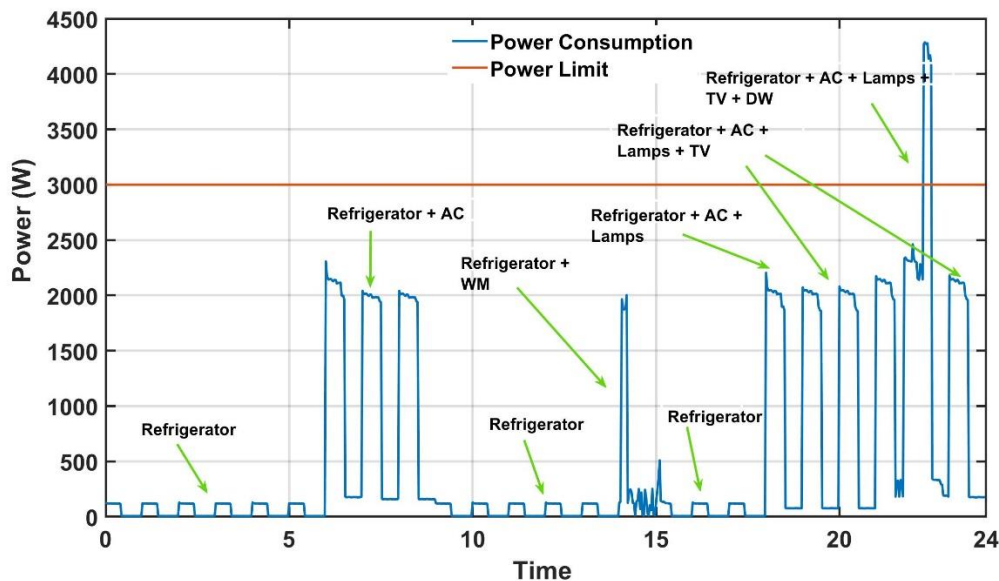

Figure 8: Evaluation of total power consumption for uncontrolled case – Scenario2
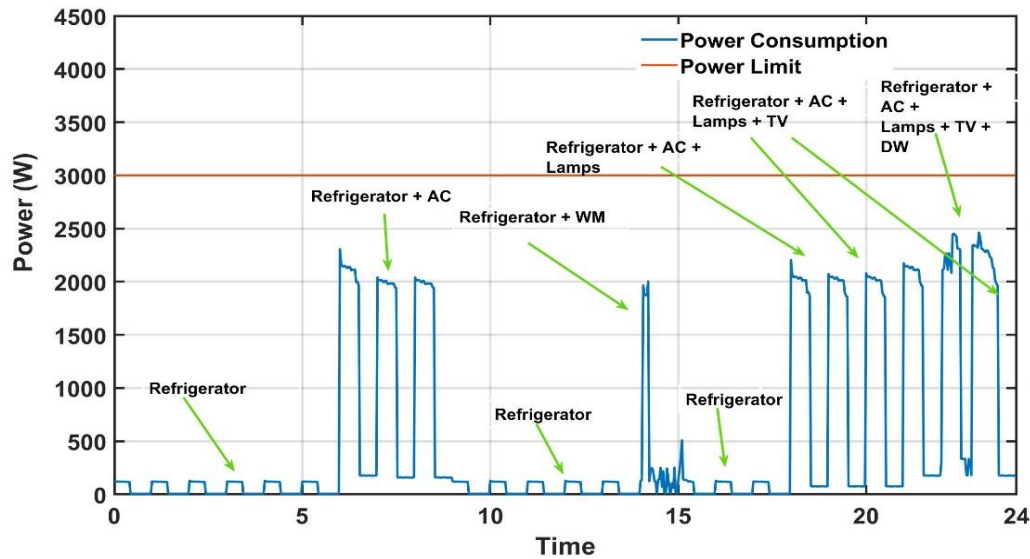
Figure 9: Evaluation of total power consumption for controlled case – Scenario2

According to the results of numerous scenarios (more than 100) carried out above, HACS completely avoids all high peak demands exceeding the specified grid limit by reducing the peak demand levels by approximately 40.4%. Furthermore, electricity costs could be reduced by 6.20%. In Table 2, these values are given.

Table 2: Results of Scenarios

Method	Electricity Cost Reduction	High Peak Demand Avoidance	High Peak Demand Reduction
Scenario-1	*3.10%*	*100%*	*37.41%*
Scenario-2	*9.06%*	*100%*	*42.56%*
⋮	⋮	⋮	⋮
Average of all scenarios(more than 100)	*6.20%*	*100%*	*40.40%*

4. Conclusion

Due to the economic development, increase in global population, and widespread use of technological devices, there has been rapid rise in energy demand recently. Beside the increase in total energy demand, instantaneous high peak demand which causes overload and costly malfunctions in the power grids. In homes where there is a significant amount of electricity consumption, the importance of efficient and controlled use of electricity is increasing.

In this work, a home energy management system based on appliance control for preventing high peak demand and reducing electricity cost while keeping user comfort, namely HACS, and the corresponding algorithm are introduced. HACS consists of a home equipped with smart appliances, grid, communication network and MC. Appliances are separated as controllable, semi-controllable and uncontrollable according to their effects on user comfort. MC is not allowed to interfere with uncontrollable appliances, but with semi-controllable and controllable appliances as much as it is permitted. MC communicates with appliances at the beginning of fixed time intervals and takes the status request of appliances. When it is necessary for preventing high peak demand, MC is allowed to interfere with semi-controllable appliances via shifting their operation and controllable appliances via switching their operation mode. Interference decision is made based on the expected power consumption and the grid limit. If interference is necessary, it is done in the order of appliance priority previously defined by the user according to his preferences.

Unlike most studies in the literature, HACS considers keeping user comfort, avoiding high peak demand and reducing the electricity cost simultaneously. Besides, real power consumption profiles of appliances are used instead of their average powers assuring to detect even short-term peak demands.

In order to show the effects of HACS, several scenarios are designed and corresponding simulations are performed. According to the results of these simulations, HACS completely avoids all high peak demands exceeding the

specified grid limit by reducing the peak demand levels by approximately 40.40%. Furthermore, electricity costs could be reduced by 6.20%. Simulation results demonstrate the effectiveness of the HACS on cost reduction and preventing high peak demand while keeping user comfort.

Acknowledgment

Nomenclature

Symbol	Description	Symbol	Description
t	time slot	t_s^a	earliest starting time of an appliance $a \in L$
T	the set $\{1, 2, ..., T\}$ of time slots	t_f^a	latest finishing time of an appliance $a \in L$
T	the number of uniform time slot in a day	Δ^a	operation duration of an appliance $a \in L$
Δ_t	the length of each time slot t	$P_{\lim}^{grid}$	grid limit
a	appliance	$P_{\exp}(t)$	expected power consumption of appliances
L	the set of appliances	a_i	i[th] prioritized appliance
L_{UC}	the set of uncontrollable appliances	P	the priority order vector $\left[a_1, a_2, ... a_{|L_C \cup L_{UC}|} \right]$
L_{SC}	the set of semicontrollable appliances		
L_C	the set of controllable appliances		

Conflict of Interest

No conflict of interest was declared by the author.

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