Energy 114 (2016) 693–707

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Appliance based control for Home Power Management Systems

Hanife Apaydın Özkan

Anadolu University, Department of Electrical and Electronics Engineering, 26555, Eskisehir, Turkey

ARTICLE INFO

Article history:
Received 17 November 2015
Received in revised form
28 June 2016
Accepted 4 August 2016

Keywords:
Home power management
Smart appliance
Petri nets
Control
Simulation

ABSTRACT

This study scrutinizes energy-friendly smart home appliances (hereafter 'smart appliances'), control of these appliances and their effects on the efficient use of energy. To accomplish this, smart appliances and their operation principles are introduced and their energy savings compared to conventional appliances are analyzed using precise measurements. Then, a real-time Appliance-based Home Power Management System (Ab-HPMS) which manages power consumption of smart appliances and that of the house as a whole is proposed. For Ab-HPMS, an appliance control algorithm, called Appliance-based Rolling Wave Planning (Ab-RWP), is developed with the aim of reducing electricity cost and improving energy efficiency while maintaining user comfort. Ab-RWP algorithm interacts with appliances in a priority order based on user comfort which is determined by utilizing their smart operational characteristics. Operations of smart appliances and their integrations with Ab-HPMS are modeled with Petri nets to verify that they meet the requirements expressed in the specifications. Simulation results demonstrate that proposed Ab-HPMS provides improvements in terms of the energy consumption reduction of about 5%–16%, cost reduction of about 10%–24% and peak reduction at high demand period of about 38%–53% compared to conventional appliances usage.

1. Introduction

Increasing population, urbanization, industrialization and technological developments in the world have increased energy consumption intensively. Increasing energy use is causing problems including depleting energy sources and creating pollution due to energy production process. For the solution of these basic energy issues, traditional grids are being transformed into *Smart Grids*, which could be defined as the grid infrastructure that optimize the energy efficiency while lowering both energy sources' installation expenses and pollution effects on the environment.

An important component of Smart Grid is *Demand Side Management* (DSM), which manages the consumption of energy to optimize energy use providing significant economic, reliability and environmental benefits. DSM allows customers to adjust their electricity usage to reduce or shift their energy consumption in response to energy availability and network constraints. Hence, participation of customers in DSM is crucial for the efficiency of Smart Grid [1,2].

In order to encourage consumers to participate voluntarily in DSM program, to reduce peak demand and to balance the power consumption in residential areas economically, energy traders apply different pricing schemes; such as, Real Time Pricing (RTP), Time of Use Pricing (TOU) [3]. In this work, TOU which is the most commonly utilized form of time-variant pricing will be considered.

Home Energy Management Systems (HEMSs) are main tools for DSM automation, which provides significant opportunities for both consumers and energy traders. Several papers have focused on offline HEM approaches. To reduce the energy cost for the customers, these studies have scheduled the home appliances or energy resources using different methods.

For example, a genetic algorithm based electricity usage scheduling method [4] is proposed for reducing electricity charge of smart buildings equipped with smart devices, while in Refs. [5], a decision support tool based on particle swarm optimization is used to generate the schedules for multiple energy resources to maximize the net benefits gained from energy services. Both peak to average ratio and electricity cost are reduced in Ref. [6] by a game theoretic energy consumption scheduling method. But, userâs satisfaction degree is not considered as an objective in these works. Besides, some studies aim to increase user comfort level as well as reducing the costs. A metaheuristic Tabu search is utilized for energy management formulated as a scheduling problem with the objectives of cost and user comfort criteria in Ref. [7]. On the other hand, multi-objective mixed integer nonlinear programming [8]

E-mail address: hapaydin1@anadolu.edu.tr.

http://dx.doi.org/10.1016/j.energy.2016.08.016
0360-5442/

Nomenclature

P	set of places in a Petri net
S	set of transitions in a Petri net
N_{ij}	i^{th} row and j^{th} column entry of matrix N
$N_{:j}$	j^{th} column of matrix N
$\mathscr{N}$	set of nonnegative integer numbers
t	time slot
T	Number of uniform time slots in a day
$\mathscr{T}$	The set of time slots $\{1,2,\ldots,T\}$
Δ_t	length of each time slot t
$\mathscr{L}$	set of appliances
$\mathscr{L}_{UC}$	set of uncontrollable appliances
$\mathscr{L}_{SC}$	set of semi-uncontrollable appliances
$\mathscr{L}_{C}$	set of controllable appliances
$\mathbf{m}^a(t)$	status vector of appliance a at time slot t
$\mathbf{m}^a_w(t)$	working mode vector of appliance a at time slot t
$\mathbf{m}^a_p(t)$	program mode vector of appliance a at time slot t
$\widehat{\mathbf{m}}^a(t)$	requested status vector of appliance a at time slot t
$\widehat{\mathbf{m}}^a_w(t)$	requested working mode vector of appliance a for time slot t
$\widehat{\mathbf{m}}^a_p(t)$	requested program mode vector of appliance a for time slot t
$\tilde{\mathbf{m}}^a_w(t)$	interfered working mode vector of appliance a for time slot t
$\tilde{\mathbf{m}}^a_p(t)$	interfered program mode vector of appliance a for time slot t
$n^a_{i_{max}}$	maximum number of interruptions of appliance a at program mode i
$T^a_{i_{max}}$	maximum interruption duration of appliance a at program mode i [min]
$T^a_{i,k}$	duration of the k^{th} interruption at the program mode i of the appliance a [min]
t^a_s	starting time of the operation of an appliance a
T^a_i	duration of the operation of program mode i of appliance a [min]
$P^{s-WM}_{den}(t)$	power density of washing machine at time slot t [W]
P^{s-WM}_{mean}	mean power consumption of washing machine [W]
$P^{grid}_{lim}(t)$	grid limit at time slot t [W]
P^{grid}_{max}	maximum power that can be drawn from the grid according to the contract between the resident and the energy trader [W]
$\widehat{t}$	internal time slot of appliances ($\Delta_{\widehat{t}} = \Delta_t$) [min]
$p^a_i(\widehat{t})$	average power consumption of the program mode i of the appliance a at its $\widehat{t}^{th}$ internal time slot [W]
$\mathscr{T}^n_t$	Time interval for next n time slots $[t\ t+n]$
$P^{\mathscr{L}}_{exp}(t)$	expected power demand of household for t [W]
$P^a_{exp}(t)$	expected power consumption of appliance a for t [W]
t^a_{int}	total number of interruptions by the current time slot
$m^a_p(t,i)$	i^{th} element of the program mode vector $\mathbf{m}^a_p(t)$ at time slot t
t^a_{sd}	earliest start time of appliance $a \in \mathscr{L}_C$
t^a_{fd}	latest finish time of appliance $a \in \mathscr{L}_C$
t'^a_{sd}	earliest start time of appliance $a \in \mathscr{L}_C$ after RP process
t'^a_{fd}	latest finish time of appliance $a \in \mathscr{L}_C$ after RP process
t^a_s	real start time of appliance a
t^a_f	real finish time of appliance a
t^{exp}_s	start time of expensive tariff period
t^{exp}_f	finish time of expensive tariff period
p^a_{sb}	*standby* power of appliance a [W]

and linear programming [9] methods that consider a meaningful balance between energy savings and user comfort are developed for optimal energy use in homes. Real time price-based scheduling approaches using appliances' time of use probabilities [10] and different demand response programs [11] by considering user comfort also exist in the literature.

The above mentioned studies seem impractical, since power consumptions of appliances were assumed to be constant or piecewise constant. In order to exhibit more realistic approaches, it is necessary to investigate specific properties and real power profiles of appliances in detail. Due to this fact, development of physical based load models at the appliance level that consider physical and operational characteristics of different load types is presented in Ref. [12]. Not the models but load profiles and associated raw data of major household appliances are given in Ref. [13] with their demand response opportunities. The work [14] investigates mathematical model and DSM potential of the refrigerator by considering the measurements collected from real devices. Furthermore, real power profiles of appliances or physical based load models are used in some HEMS approaches. Through the works using real power profiles of appliances [15], presents a wireless communication structure to reduce electricity cost and peak demand values, and to increase consumer comfort by interacting with users; while [16] proposes voltage control without turning off any appliance. Apart from these [17], proposes physical based load models for electric loads and presents an approach to solve the peak shaving problem that leverage the real-time scheduling discipline to coordinate the activation and deactivation of these loads. Likewise [18], uses the physical based model, which was presented in Refs. [12], to test their HEM algorithm that manages household appliances by taking appliance priorities into account [19]. also uses appliance priorities for the presented dynamic load management algorithm that manages appliances and power resources during demand response events. Instead of appliance priorities, resource priorities are considered in HEMS developed in Ref. [20]. In that paper, a real time HEMS named RTHPMS is presented for reducing electricity cost via resource prioritization and simultaneous interference with smart appliances without exploiting their beneficial potential.

The above mentioned works have contributed to the performance of HEMS with innovative approaches. However, in those studies integration of smart appliances with HEMS is not handled and the advantages of using smart operational characteristics of these appliances are not considered. Whereas, by the integration of smart appliances, a more advantageous HEMS can be designed when compared to conventional appliances from the view of user comfort, electricity cost and energy efficiency. Furthermore, knowing the operational principles and taking this knowledge into consideration when developing a HEMS, can make it possible the system to produce more efficient and precise solutions.

Operating characteristics of smart appliances are examined in detail and a control approach is developed according to these characteristic properties. For this purpose, smart appliances and their operation principles are introduced and their energy savings compared to conventional appliances are analyzed using precise measurements. Furthermore, a real time Appliance based Home Power Management System (Ab-HPMS) is proposed, which manages energy consumption of smart appliances and that of the house