Energy 113 (2016) 301–308

Contents lists available at ScienceDirect

Energy

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

Residential demand response scheme based on adaptive consumption level pricing

Haider Tarish Haider [a, b, *], Ong Hang See [a], Wilfried Elmenreich [c]

[a] Department of Electronics and Communication Engineering, Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, 43000, Kajang, Selangor, Malaysia
[b] Department of Computer and Software Engineering, University of Al-Mustansiriyah, 10001, Baghdad, Iraq
[c] Institute of Networked & Embedded Systems/Lakeside Labs, Alpen-Adria-Universität Klagenfurt, 9020, Klagenfurt, Austria

ARTICLE INFO

Article history:
Received 11 March 2015
Received in revised form
14 February 2016
Accepted 10 July 2016

Keywords:
Smart grids
Demand side management
Residential demand response
Advance metering infrastructure

ABSTRACT

Demand response aims to change the energy consumption patterns of normal customers in response to changes in price rate or incentive offers. This process reduces peak loads and in turn potentially lowers the energy cost for customers. In this study, we propose a new demand response scheme on the basis of an adaptive consumption level pricing scheme. On the one hand, this strategy encourages customers to manage their energy consumption and consequently lower their energy bill. On the other hand, it allows utilities to manage the aggregate consumption and predict load requirement. Unlike other pricing schemes, such as block tariff and time-of-use, the proposed pricing scheme can lower the energy bill of about 73% of customers, assuming that the total utility revenue is the same for all pricing schemes. On the basis of the currently available schemes in the literature, we find that the proposed method has significant advantages over other schemes in terms of fairness in charging customers.

1. Introduction

Many serious blackout crises have occurred in traditional power grids, such as those in the U.S. and Canada in 2003, Italy in 2003, and Indonesia in 2005 [1]. For the majority of the cases, the blackouts are caused by over-demand from consumers during peak period [2]. The increasing number of households, the higher level of comfort and the higher number of domestic appliances led to a world-wide increase of energy consumption in the residential sector [3] of around 30–40% of total consumption [4]. The traditional solution is to these problems has been increase generation capacity (e.g., building additional conventional coal-fired power plants). However, increasing the supply capacity via continuously building conventional power plants is unsustainable because it is costly in terms of capital expenditure [5], its operational cost is high as a result of fossil fuel depletion [6], and it increases greenhouse gas emissions that contribute to climate change [7].

The recent integration of information and communication technology (ICT) systems has transformed the traditional power grid into a smart grid [8]. ICT systems enable the efficient use of energy by deploying intelligent devices and control systems to automate power grids [9]. Furthermore, advanced communication systems contribute to the interaction between utility companies and customers. Consequently, customers are able to save energy and cost while utility companies are able to maintain system reliability and resilience [10].

Demand side management (DSM) or load management [11] optimizes energy consumption and cost by shifting loads away from peak periods [12]. Demand side management is a key feature of a smart grid [13]. Demand side management employs ICT, such as Internet of Things, for load monitoring and for optimally carrying out load management in near real time. With two-way communication, customers can follow price changes and incentive offers to make decisions on energy consumption accordingly [14].

Demand side management covers two main functions of a smart grid, namely, maintaining energy efficiency and executing demand response scheme [15]. Typically, these two functions are implemented individually as programs in a utility company, with demand response serving as the major module in demand side management [16]. A demand response scheme essentially reduces or shifts customer load during peak periods to avoid energy cost increment and to stabilize the grid [17]. Several studies have been conducted to look at the cost and benefits of demand response systems as in Ref. [18] and the peak energy reduction as in Ref. [19].

* Corresponding author at: Department of Electronics and Communication Engineering, Universiti Tenaga Nasional, P13-B-07-06 Sri Cempaka, Jalan Sepakat Indah 2/2 Taman Sep, Kajang 43000 Selangor, Malaysia. Tel.: +60 183262643.
E-mail addresses: haiderth@ymail.com (H.T. Haider), ong@uniten.edu.my (O.H. See), wilfried.elmenreich@aau.at (W. Elmenreich).

http://dx.doi.org/10.1016/j.energy.2016.07.052
0360-5442/

In recent years, demand response has expanded to include residential sectors in addition to commercial and industrial sectors by using advanced metering infrastructure based on dynamic pricing [20]. Residential demand response has become an important research area because of the many challenges involved in the implementation of demand response in this sector in terms of analyzing the response of customers from the econometrics perspective [21], efficient interconnection of consumers, electric cars, microgrids [22], and the complexity of the home management systems [23].

Residential load and tariff management can be categorized into two types, namely, incentive- and price-based schemes [24]. In an incentive-based scheme, a utility company offers to manage loads during emergency or peak periods based on a mutual agreement. A popular demand response incentive program is direct load control. In this program, the utility company can access and control the appliances of customers and receive monetary rewards in return [25]. This approach of direct access to customer premises for on/off operation is very invasive. The lack of customer privacy [26] and system scalability are the major drawbacks of direct load control and other incentive-based programs [1].

In a price-based scheme, customers are able to adjust their energy usage in response to the utility pricing signal [27]. The customers are encouraged to individually manage their loads by either reducing or shifting their energy consumption from peak hours to less congested hours, thereby favoring load balancing. Popular programs in a price-based scheme include time-of-use pricing (ToU), critical peak pricing, and real-time pricing [28]. In general, the energy price changes with time in every program [29]. For example, in time-of-use pricing, the price of energy varies for different times in a day and different seasons in a year [30]. The utility company changes the time-of-use according to the available power supply and predicted customer demand. Even though price-based schemes do not have customer privacy and system scalability problems, offering a price rate for a specific time period to all customers is unfair to those who already have a normal or low level of consumption. This problem arises from the externality effects of the energy usage of higher consumption consumers' (selfish customer) that are imposed on the price rate for other customers. Following price changes at different time periods may also be confusing to customers. Moreover, a schedule mechanism, either manual or automated, is needed to help customers manage the load [31].

At present, the majority of residential consumers of electricity in developing countries are offered a service with a flat tariff scheme. A flat tariff charges a uniform price for each unit of electric energy. This system does not provide customers with incentives to modify their consumption behavior in periods of rising electricity production costs [32]. The residential electricity block tariffs have been adopted in many countries, such as the U.S., Japan [33], China [34], and Taiwan [35]. However, electricity block tariffs still lead to certain welfare leakages in a way that block tariffs might penalize residential customers that have large family with many members, which will consequently affect social equity [33].

Most incentive demand response programs have been used for emergency cases or for controlling the cycling of customer air conditioners. Examples of existing incentive demand response programs in the U.S., in which the customers receive load control signals, include the PG&E SmartAC program, the energy thermostat program of Southern California Edison, and the smart thermostat program of the San Diego Gas & Electric Company [19]. However, these programs do not address the peak load problem [36].

Price-based schemes, where customers respond to a time-varying electricity tariff, have been examined in Ref. [37]. In this study, the price signal is suited to the intention of obtaining good customer response, especially with regard to high prices. Moreover, the time-varying prices present substantial potential for increasing customers' welfare [38]. In the U.S., time-of-use pricing is widely available from utility companies; approximately 150 entities provide different time-of-use pricing programs [39], such as the PowerCentsDC program, the voluntary time-of-use rate offered by the Sacramento Municipal Utilities District [19]. In France, the Tempo tariff of Électricité de France has targeted the residential sector. It is a time-of-use tariff that charges different electricity prices for different days in the year; such prices are divided into three color-coded price categories (300 days are blue − low electricity prices, 43 days are white − medium electricity prices, and 22 days are red − high electricity prices) [40]. SmartHG [41], is a European-funded project for a real-time demand response scheme. The aim of this project is to help customers and the utility company to manage energy consumption. In Refs. [42], a real-time program framework is proposed to generate feasible real-time curves for customers in a demand response management process. Most recent studies of real-time program use the day-ahead real-time pricing as basis. However, the hourly real-time pricing has been argued to be a more efficient method of engaging customers in smart grids [42]. In Refs. [43], a critical peak pricing scheme is designed for profile maximization, considering the price responsiveness of customers. In this study, the effect of critical peak pricing parameters on customer profit based on the price responsiveness model is analyzed.

In summary, the existing schemes of the residential demand response lack critical features, such as customer incentives and social equity of flat and block tariffs schemes, customer privacy and system scalability for incentive-based schemes, and an automated mechanism that follows price changes with respect to time periods, externality effect, and load synchronization for price-based schemes. The purpose of this paper is to fill this gap and to propose a new demand response scheme that can overcome the drawbacks of the current residential demand response schemes based on the adaptive consumption level pricing scheme (ACLPS).

The adaptive consumption level pricing scheme is based on two complementary factors, namely, adaptive pricing for the consumption level of each individual consumer and consumption allowance (CA). The proposed demand response scheme satisfies the requirements of both the customers and the utility companies. As will be discussed later, utility companies maintain grid reliability and sustainability while customers obtain a significant decrement in energy cost without encroachment to their privacy.

Specifically, the proposed scheme provides customers with an adaptive level of energy consumption pricing over different load operation periods, and it is based on the monitoring of the energy rate of customers. Under the proposed scheme, the pricing through time is simple for customers, who are provided with optimum prices according to the limits of the band of energy consumption.

The rest of the paper is organized as follows. Section 2 provides modeling of the proposed demand response scheme. Section 3 presents the simulation results. Section 4 discusses the conclusion of the study and recommendations for future work.

2. Modeling of the proposed demand response scheme

The proposed scheme adopts price rate and consumption allowance (CA) according to two factors, namely, consumption period and consumption level. In the proposed demand response scheme, the utility company provides multiple levels of price rate that correspond to the level of average consumption (Fig. 1). Each level has a consumption allowance associated with it. A price invariant band (PIB) is double the consumption allowance or ($\pm$CA) around the consumption level. Consumption allowance has two types, namely, positive consumption allowance (CA^+) and negative consumption allowance (CA^-). A positive consumption allowance is