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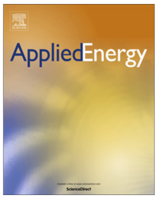

User satisfaction-induced demand side load management in residential buildings with user budget constraint

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HIGHLIGHTS

- DSM scheme that could maximize satisfaction within user's budget is presented.
- Load-satisfaction algorithm using the scheme is developed based on GA.
- We quantified user satisfaction based on certain rules.
- We develop cost per unit satisfaction index, *k*($) that relates budget to satisfaction.
- The proposed algorithm is effective in offering the maximum satisfaction.

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ABSTRACT

This paper presents a demand side load management technique that is capable of controlling loads within the residential building in such a way that the user satisfaction is maximized at minimum cost. Load-satisfaction algorithm was developed based on three postulations that allow satisfaction to be quantified. The input data required by the algorithm includes the power ratings of the electrical devices, its time of use, kW h electrical consumption as well as the satisfaction of the user on each electrical appliance at every hour of the day. From the data, the algorithm is able to generate an energy usage pattern, which would give the user maximum satisfaction at a predetermined user-budget. A cost per unit satisfaction index (k) which relates the expenditure of a user to the satisfaction achievable is also derived. To test the applicability of the proposed load-satisfaction management technique, three budget scenarios of $0.25/day, $0.5/day and $1.00/day are performed. The result of each of the scenarios using the proposed techniques is compared to cases in which the electrical appliances are randomly used. The results obtained revealed that the proposed algorithm offered the maximum satisfaction and minimum cost per unit satisfaction for all the scenarios.

1. Introduction

Over the years, research has been focussed on different technological strategies to meet up with the increasing demand for high quality and reliable power supply. Prominent of these researches is electrical energy conservation and management. The management of electricity can be categorized into two broad classes: the Supply Side management (SSM) and the Demand Side management (DSM). The SSM refers to actions taken to ensure the generation, transmission and distribution of energy are conducted efficiently [1,2]. It is used by utility companies to ensure reliable availability of energy at the minimum economic cost with the aim of increasing profits [3]. On the other hand, demand side management (DSM) programs consist of the planning, implementing, and monitoring activities of electric utilities which are designed to encourage consumers to modify their level and pattern of electricity usage [1,4]. Usually, the goal of DSM is to encourage the consumer to use less energy during peak hours, or to move the time of energy use to off-peak times such as night-time and weekends. Since DSM has cost benefits, it has been adopted on a large scale by consumers for their home energy management [5,6].

Many DSM techniques have been identified in [7]. Some of them are the load priority techniques, the end use equipment control techniques, the peak clipping valley filling techniques and the differential tariff. Moreover, different energy management algorithms have been proposed in order to make building smarter with the general aim of minimizing the daily energy cost without affecting the comfort of the house owners [8,9]. Missaoui et al. [10] analysed

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the performance of a global model based anticipative building energy management system (GMBA-BEMS) in managing household energy consumption. The authors succeeded in reducing the cost of electricity by using the model to manage home appliances. Similarly, Alagoz et al. [11] proposed a closed-loop PID control system for real time balancing of energy demand and generation in a smart grid electricity market. The system has the capability to regulate energy prices online to respond dynamically and instantaneously to the varying energy demand. Similarly, Murphy et al. [12] utilized a DSM algorithm for the optimization of ice storage in a dynamic real time electricity pricing environment. The authors also succeeded in reducing the cost of electricity via the algorithm.

While the aforementioned authors primarily focused on the cost of electricity in their different works, some other authors have used the time of device operation as their main objective. For instance, Di-Giorgio and Pimpinella in [13] worked on smart home controller which can determine the best time to run a smart household appliance. The controller was based on binary linear programming. Similarly, an analysis based on Monte Carlo simulation was utilized to study the residential demand response in Yinchuan, China by Yongxiu et al. [14]. The study revealed that suitable designed time of use (TOU) rates are useful to the efficient operation of a smart grid. Also, Gruber et al. [15] proposed and developed a model for generation of residential energy consumption profile based on the energy demand contribution of each household appliances using probabilistic approach. Their model provides a high modular structure that gives a high degree of flexibility. From the various studies, one can deduce that effective load management has a positive correlation with energy efficiency and electricity bill. In Soares et al. [16], a multi-objective genetic algorithm was used to solve a multi-objective model to optimize the time allocation of domestic loads within a planning period of 36 h in a smart grid context. The authors also minimized the electricity bill of a household by the management of controllable domestic load.

In the issue of load management, comfort and satisfaction of users are of significant concern. Some authors have worked in the area of comfort management and user's satisfaction in buildings [17,18]. Comfort conditions and the quality of life in buildings have been assessed by three basic factors: the thermal comfort [19], visual comfort [20] and the indoor air quality [21]. Thermal comfort is determined by Predictive Mean Vote index which predicts the mean thermal sensation vote on a standard scale for a large group of persons [19]. Mathematical model was developed for automatic analysis and diagnosis of environmental thermal comfort in energy efficient buildings and presented in Balvís et al. [22]. The authors are of the opinion that the model could serve as diagnostic tools that could be combined with actuators in order to optimize energy savings in buildings while maintaining comfort. Korkas et al. [23] proposed an algorithm for intelligent energy and thermal comfort management in grid-connected microgrid with heterogeneous occupancy schedule. In their study, they optimized both the energy cost and thermal comfort. It was revealed that the algorithm was able to automatically changes the energy demand of buildings in accordance to occupant behaviour. In another work, A novel control algorithm for joint demand response management and thermal comfort optimization in micro grids equipped with renewable energy sources and energy storage units was studied by Korkas et al. [24]. The proposed work covered two objectives: the first is the matching of energy generation and consumption with the occupant behaviour and with the objective of guaranteeing thermal comfort of the occupants. The second objective is the development of a scalable and robust demand response program. The effectiveness of the proposed method was validated in a microgrid which composed of three buildings, a photovoltaic array, a wind turbine and an energy storage unit. Similarly, yang and Wang [25] developed a multi-agent system for building energy comfort management based on occupant behaviour. The authors were of the opinion that the developed multi-agent system has the capability to facilitate the building to interact with its occupant for realizing better user satisfaction. A simulation tool (QUICKcontrol) that could determine the effect of changing control strategy on indoor comfort and energy consumption in buildings has been developed by Mathews et al. [26]. The authors demonstrated that the tool has the capability to predict building energy savings of 34% per annum. A comprehensive understanding of energy use during building operation and how it influences user comfort was investigated by Lawrence and Keime [27]. The author highlighted the significance of occupancy pattern to the understanding of energy efficiency and comfort. Their findings illustrated how comfort could be improved by increasing the degree of environmental control that occupants have without necessarily increasing energy consumption.

Visual comfort is determined by how the illumination level measured in lux affects user satisfaction in buildings [19]. Yun et al. [20] investigated the lighting energy consumption of open plan offices in relation to visual comfort and close relationships between prevailing illuminance levels on the work plane and luminous comfort was established. Acosta et al. [28] have performed the analysis of energy savings for lighting and visual comfort in residential spaces with different window architecture design. They quantified visual comfort in a residential room for different window models. It was concluded that window size is not relevant for energy savings. However, the windows located higher up resulted in higher illuminance at the back of the room than those in centred locations. Energy and visual comfort analysis of lighting and daylight control strategies has been performed by Shen et al. [29]. In their work, improved independent and integrated control strategies were proposed by adding shared HVAC state and occupancy information. It was established that integrated lighting and daylight control outperforms all other strategies in energy and visual comfort performance.

Indoor air quality is quantified by the carbon dioxide (CO_2) concentration in a building [19]. The CO_2 concentration arises from the activities of the inhabitants in a building and from various other sources of pollution. An overview of indoor air quality and energy management through real-time sensing in commercial buildings was carried out by Kumar et al. [30]. It was revealed that some of the attempts to conserve energy are found to exacerbate unacceptable indoor air quality. The authors are of the opinion that the rise of sensing technology over the past decade has shown potential to address air quality issues.

In view of the different considerations of comfort conditions and its application to load management, this paper further considered the dimension of user satisfaction from the view of time- and device-based satisfaction to evaluate absolute satisfaction for the users. Usually, electricity consumers are faced with several constraints in their attempt to use electricity. Prominent of these constraints are the need to derive maximum satisfaction from electricity usage and the need to use electricity within the user's budget. These two constraints are oftentimes opposing. For instance, in the bid to maximize satisfaction, a user could either use more electrical appliances or use the same appliances for longer hours. However, this act implies more energy demands hence more cost implications. It is intuitive to believe that a DSM program would influence the load consumption pattern and the energy cost of consumers. It could also affect their level of comfort and satisfaction. Since a high quality of life through the use of clean and affordable electricity is always the desire of man, it is therefore important that a DSM program takes into account the load consumption pattern, its cost implication to the consumer as well as its impact on the consumer's satisfaction. Thus, this paper develops an algorithm that is capable of generating an energy usage pattern,