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An equitable and efficient energy management approach for a cluster of interconnected price responsive demands

Ali Reza Vahabi[a], Mohammad Amin Latify[a,*], Morteza Rahimiyan[b], G. Reza Yousefi[a]

[a] Department of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran
[b] Department of Electrical Engineering, Shahrood University of Technology, Shahrood 36199-95161, Iran

HIGHLIGHTS

- To consider equity in energy allocation (EA) to a cluster of demands.
- To model EA as a bilevel optimization problem and convert it to a single-level one.
- To obtain an EA which possesses the maximum equity while observing efficiency.
- To investigate externalities impacts on the obtained EA.
- To analyze the sensitivity and robustness of the obtained EA.

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ABSTRACT

Equitable and efficient allocation is one of the basic principles in all energy management systems. Classic allocation methods tend to maximize the customers' total surplus to achieve the maximum possible efficiency. From the perspective of equity, there are some elements of ambiguity in this approach. In this paper, a new approach is proposed to allocate consumed energy to the customers aimed at holding equity, while achieving maximum possible efficiency is taken into account. For this purpose, the energy consumption allocation is studied for a cluster of interconnected price-responsive demands (i.e., a group of loads, such as an industrial compound, which are interconnected to each other in a geographical area and also to the main network via a local electrical network). A centralized energy management for a cluster of members is a cooperative game. In this paper, the equilibria of the cooperative game are determined by solving a multi-objective optimization problem, constrained to the constraints of the local electrical network operation and also the demands constraints. The solution of this optimization problem results in a Pareto front of which each point represents an equilibrium of the cooperative game. Then, an equilibrium is selected based on the proposed equitable allocation. The nature of the proposed model is a bi-level optimization problem. In the first level, the optimization problem of selecting an equilibrium is formulated. In the second level, a multi-objective optimization problem is modeled to calculate all equilibria of the cooperative game. Accordingly, the energy consumed by demands is allocated through the proposed centralized energy management system which is established based on equity and efficiency. The results obtained from a test system show the advantages of the model in performing energy management for a cluster of price-responsive demands.

1. Introduction

In the past decades, electrical energy demand growth has resulted an increase in its price, as well as in the pollutions produced by the generation units. Under these conditions, energy management at the level of demands has attracted a great attention. The main goal in energy management is to increase the efficiency in consuming energy, which reduces the cost of energy and indirectly reduces the level of pollutions as well [1,2].

Basic requirements for managing energy in electrical networks include a bidirectional communication infrastructure and decision-making tools. The first requirement will be fulfilled by developing the smart grid technologies [3]. Designing decision-making tools for demands is a challenging subject under debate, and it is also the main concern of this paper.

Based on the basic principles of economics, one of the key concepts

* Corresponding author.
E-mail address: latify@cc.iut.ac.ir (M.A. Latify).

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in every allocation problem with economic objectives is to achieve both equity and efficiency simultaneously. Hence, it is necessary to consider these two criteria, simultaneously, in allocating energy to the demands. In economics, equity and efficiency are defined as follows:

Efficiency: A maximal usage of resources in a society is called *efficiency* [4]. In other words, if resource allocation to the members of a society maximizes the benefit or total surplus of that society, then the allocation is efficient.

Equity: A fair distribution of the benefits resulted from a society's resources, among the members of that society, is called *equity* [4]. In other words, an allocation is fair and equitable when no member of a society prefers the benefit or surplus of the others to its own [5].

As members of a society attain non-equitable benefits or surpluses from equal resources (due to their different features and characteristics), an attempt to achieve equity results in a reduction in the society's efficiency. Hence, a fair and equitable allocation costs the society. Accordingly, it is not possible to achieve to an absolute equity and efficiency in an allocation at the same time and, as a result, a trade-off should be considered between these two objectives [4,6]. By defining a society as a set of demands involved in an energy management program, such as the ones in an industrial compound, and the energy as the allocable resource, this challenge is observed in the energy management problem. In this paper, in addition to explaining this issue in the field of energy management, a new approach is proposed to resolve it.

The concept of demand side energy management has been discussed in literature in decentralized, centralized and quasi-centralized manners. The decentralized management structure mainly relies on the fact that the instantaneous price changes are shared with all the demands and, consequently, the demands start to allocate energy by using their autonomous decision-making tools. These studies commonly use the game theory and the agent-based simulation [7–9] for analyzing the demands behavior. In the centralized energy management method, demand incentive mechanism is provided by setting tariff incentives, allocating penalty/incentive to the demands when they conflict/meet their obligations [10], or by direct load control via a central organization (e.g., the local electrical network operator or the independent system operator) [11,12]. The centralized energy management method generally relies on modeling the energy allocation problem as an optimization problem. In the quasi-centralized energy management method, the centralized and decentralized methods are integrated [13]. Further detailed investigation of literature in the field of energy management approaches is provided as follows.

(A) Decentralized energy management

Initial studies on decentralized energy management have been commonly concentrated on coordinating the functionality of demand energy management units [14–16] with different objectives such as minimizing the generation costs or minimizing the ratio of network peak to mean load. Most of these studies use mechanisms that do not consider the demands participation or miss-participation in the game, fairness, or equity; because the cost paid by each demand is only proportional to its total energy consumption. This flaw would give the demands a feeling of unfairness. For this reason, the authors in [17] have investigated different factors such as seasonal demand changes, load shifting, and load adjusting that make the demands feel unfair. In [18], fairness is assessed from a social point of view. In this approach, demands payments for electricity are proportional to their income. A billing mechanism is proposed in [7] which tends to minimize the overall system cost. This mechanism does not accurately consider the load profile of each demand. To overcome the problem of inequity and unfairness in this framework, an alternative billing mechanism is used in [19] and [20]. Herein, the exact load profile, as well as the flexibility of each demand is taken into account. These considerations improve the fairness and the equity in energy allocation. The actions and mechanisms for protecting the demands privacy when using this billing mechanism, are evaluated in [21].

To improve the policy of encouraging users to shift their load profiles, the Shapley value is approximated to fairly allocate the costs of a micro-grid to the users involved in the demand response (DR) program in [22]. This strategy shows a relatively better functionality with respect to the proportional billing mechanism. In [23], a game-theory-based demand-side management strategy is used as an alternative choice for the billing mechanisms proposed in [19,20,22]. Under this strategy, the additional generation cost resulting from deviation of some demands from their optimal consumption levels is also divided fairly among them.

In order to manage and encourage the electric vehicles to be charged in the off-peak hours, and to participate in the load profile peak shaving, the criterion of contribution-based fairness is proposed in [23]. This criterion decreases/increases by charging/discharging over the peak hours. The vehicles with a higher value of this criterion take higher priorities to be charged. Ref. [24] introduces an incentive-based policy aim to peak shaving via giving fair coupons to the demands in local electrical network. In this method, a distribution company would provide incentives for its demands, by giving them certain amounts of coupons, to decrease their consumption during the peak hours.

Ref. [25] designs a DR reward system based on a fairness index to encourage demands to increase DR participation levels. It defines fairness as "customers with higher participation level can reduce their individual cost more than those with lower participation level within the same community". To achieve the fairness, trading prices are customized for each demand according to a fairness index that quantify the participation level over the given time periods; however, the fairness-based reward system may not guarantee efficient distributed energy resource utilization among the demands. Ref. [26] highlights the advantages of cooperation among urban buildings that formulate a micro-grid and are able to exchange energy in order to achieve increased self-sufficiency and reduced carbon emissions. The proposed cooperative model targets the determination of the optimal capacities of the buildings' equipment. A common approach that is used for optimizing building coalitions is to minimize the total cost of all demands. However, this method may lead to an unequal distribution of the coalition benefits.

(B) Centralized energy management

All references in the field of centralized energy management have used maximization of the classic social welfare, or in other words, maximization of the efficiency, as the objective function of their optimization problem. The subjects of equity and fairness are not sufficiently addressed in these researches. In [27], an optimal load curtailment mechanism is proposed to maximize profit of the local electricity company and to compensate the costs resulting from voluntary participation of demands in this mechanism. In [11] and [12], demands consumption is directly controlled by the local electricity company. The direct load management is executed based on an agreement between the local electricity company and the demands. A general concept of DR service provider unit is introduced in [28] which offers services to the demands in a local electrical network, with the objective of maximizing all demands surplus. Energy allocation to demands within a network to maximize the value of social welfare is also investigated in [29–32]. An energy management strategy for a residential local electrical network which comprises photovoltaic systems, wind turbines and batteries is proposed in [33] in order to make a more efficient use of the batteries to achieve better purchased power profile. This strategy is experimentally validated by real data. Reference [34], develops the model proposed in [33] by using a low complexity fuzzy logic control.

To distinguish the characteristics of inflexible and flexible demands, the authors in [35] describes the interaction of several DR aggregators in a bi-level leader–follower framework in which energy scheduling problem for a demand serving entity that serves both inflexible and flexible demands is discussed. The upper-level problem aims to maximize the profit of demand serving entity and the lower level problem that is for DR aggregator wishes to maximize its payoff function (the utility minus the cost). Although the centralized approach yields the