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A strategical game theoretic based demand response model for residential consumers in a fair environment

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ABSTRACT

Demand response programs are developed to preserve the balance of demand-supply ratio and to reduce energy cost incurred by the electricity customer. Most of the existing work on residential demand response programs focused on utility-consumer interaction in a coordinating game model via two-way communication to achieve minimization of total cost and peak to average ratio. The prior work has considered the problem of energy consumption scheduling for multiple users but fails to address the optimally fair environment for scheduling. This paper proposes a consumer preference based demand response model formulated in a game-theoretic framework. The proposed model have a key feature that no consumer can acquire profit by deviating from the prescribed strategies or chronological order. The optimal game scheduling for minimizing the energy costs is achieved by using correlated equilibrium represented as Nash Equilibrium of energy consumption scheduling game. The simulation results clearly demonstrate the minimization of peak to average ratio up to 31.4% on an average for each day. The cost benefit of 261.6$ in a day is reaped by total users in the system which is highest among all days. The proof of existence of Nash Equilibrium is authenticated in the appendix.

1. Introduction

The advent of future electricity paradigm in the form of smart grid is encouraging the participation of electricity customers in the operational and market policies of power system via demand response (DR) programs. The operation of DR programs enables the interaction among electricity end consumers and utility for empowering the smart grid. DR programs are encouraging the user to become part of electricity infrastructure and being informed of energy management decisions. The DR programs is defined by U.S. Department of Energy Information [1] as, "*Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized.*"

The electricity power production is always required to maintain the load demand at all the times as electricity cannot be stored economically. DR programs are classified into two types, i.e.. incentive based and price-based programs [2]. In the incentive-based DR programs, end-customers are required to curtail their loads at the hour of need and in exchange the utility is inspired to provide certain incentives [3]. With the regulation of incentive-based programs, the procurement of flexibility can be enhanced between end-consumer and utility. For price-based DR programs time-of-use (TOU) pricing, critical peak pricing (CPP) and real-time pricing (RTP) are the main components. A different type of dynamic tariff such as inclining block rate (IBR) is introduced by BC Hydro (BH) which incorporates a two-step residential rates limited by a threshold rate over a time-period [4].

DR approach mostly focuses on load shifting of the consumer energy usage from on-peak hours to off-peak hours to manage the supply provided by the utility company. The application of DR programs is developed for the industrial and commercial customers, but at the same time, residential customer demand occupies 40% of the energy consumption in the world [5]. The DR approach in residential sectors mostly recounts to smart households, which enables a technology of home energy management (HEM) system that allows an intelligent controller incorporation with smart meter, smart home appliances, plug-in electric vehicles, and storage system [6]. The HEM system allows the consumer to manage the information and manage their appliances comfortably. The flexible demand of residential user enables the DR application in this sector which can have high potential to serve the utility and to maintain the supply-demand ratio balanced by shifting of appliances.

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Nomenclature

$n(N)$	index (set) of users in the system
$m(M)$	index (set) of appliances
$t(T)$	index (set) of time periods
$d(D)$	index (set) of days
W_t	base load at tth hour
$\widehat{\mathbb{P}}_{m,n}$	power rating of mth appliance of nth *user*
$\Delta t_{m,n}$	running duration for mth appliance of nth user
$C(W_t + \widehat{\mathbb{P}}_{m,n})$	cost of using appliance m of nth user at tth hour
$C(W_t' + \widehat{\mathbb{P}}_{m,n})$	cost of using appliance m of nth user if scheduling has occurred prior to it actually occurs
$x_{m,n,d}$	energy consumption scheduling vector of mth appliance of nth user for dth day
$x_{m,n,d}^t$	energy consumption scheduling vector of mth appliance of nth user on dth day at t time slot
tos_n	time of scheduling of user n
$W_t^{tos_n}$	base load of tth hour at time of scheduling of user n
$bfd_{m,n,d}$	balance factor of nth user for mth appliance on d day
$bf_{n,d}$	balance factor of nth user on d day
$P_{n,d}$	payoff of nth user on d day
$\mathbf{X}_{(n,d)}$	set of scheduling vector of appliances of nth user for a day d
$\mathbf{X}_{-(n,d)}$	set of scheduling vector of appliances of other user than nth for a day d

1.1. Related work

The distinct residential DR models have been actively developed by many researchers. An incentive-based energy consumption scheduling scheme is proposed in [7] which discusses the optimal scheduling approach by minimizing the energy cost in the system. In [8], a home energy management (HEM) system problem with power-intensive appliances is formulated, the HEM algorithm can control the home power consumption below certain limit imposed by the system. The main motive of these studies is to develop price-based DR programs with minimizing residential users' electricity bill payment [7–9]. A nonlinear DR model of time-based pricing is developed in [10]. An energy scheduling to achieve a trade-off between the energy bill and discomfort of residential consumers is proposed in [11]. The battery inclusion with energy scheduling problem is found in [12], where consumer is allowed to charge their batteries during off-peak periods and utilized them when energy price is high.

The classical optimization techniques and heuristic approaches have been widely implemented in the past for optimizing DR problems. A day-ahead load shifting technique using an evolutionary algorithm is proposed in [13]. In [14], a HEM system problem is formulated as the nonlinear optimization problem and solved using the genetic algorithm (GA) to minimize the peak to average ratio. A multi-consumer problem is presented in [15], and the multi-objective optimization is solved using the artificial neural network (ANN) with NSGA II. The linear programming is extensively used to solve such DR problems [16,17]. The exploration of DR problem in the format of non-convex and NP-hard problem is investigated in [18]. A heuristic gradient-based particle swarm optimization (PSO) algorithm is implemented for the purpose of smart scheduling of residential appliances. But from the literature, it is summarized that commercial software tools such as CPLEX and MOSEX are proved an effective platform to analyze DR problem.

Game theory is a computational model of interaction and competition among energy user and utility company is extensively used to DR programs. The study in [19] presents a non-cooperative demand mechanism game to minimize user expenses by producing or storing the battery energy instead just buying from the grid. Two design is developed such as to optimize separate user by formulating the grid optimization problem as a non-cooperative game other as joint optimization of the whole system allowing some cooperation among the users. A smart power system with distributed consumers seeking energy demand to the utility company is proposed in [20]. In this model, user tries to minimize for their batteries during off-peak hours and discharging the energy at peak hours. A Stackelberg game is presented in [21] between utility companies, and end-consumers to maximize the economic benefit of the utility company and user payoff. The game theory applications for DR in [7] used the players in the games that can be naturally modeled by autonomous agents. An autonomous DR model is developed in [22] that can achieve both optimality and fairness. The work on achieving fairness in DR framework is limited, perhaps fairness point of view is included in [22]. A repeated game is presented in [23] which shows the inefficiency of the Nash Equilibrium as a one-shot game, hence represented as repeated game. To incorporate the fairness among users, they are divided into groups and only one group is allowed to participate in a DR program at a time. An online long-term scheduling algorithm is developed in [24] to model the uncertain behavior of price and load demand as a Markov decision process. To make the problem tractable, each user is required to execute an algorithm to approximate the state of users.

Load shifting and load curtailment are the two mechanisms to implement DR programs. Reduction in the power consumption is obtained by motivating the consumers to adopt energy enlightened pattern [25]. On the other hand, load shifting takes advantage of time independence of loads, and shifts loads from peak time to off-peak time in order to avoid accumulated load at peak hours. Some users have their usage timings of individual appliances, which cannot be shifted. Even though shifting can provide benefit in terms of cost but comfort cannot be compromised. A human expert based load curtailment approach is investigated in [26] to model a complex decision-making process. In this approach, a load curtailment allocation is implemented by prioritizing the importance of customers and type of loads. A direct load control technique is proposed in [27] to implement a semi-automated demand response with Gaussian mixture model (GMM) for estimation purpose of load demand.

1.2. Summary of contribution

The literature reveals that use of game theory in demand response problem is a fascinating approach to deal within an interactive environment. Most of the research work in the past has dealt with the problem of interaction between user and utility but the accountancy of fairness of Nash Equilibrium is limited throughout the literature. This paper presents a game theory based DR model using correlated equilibrium. Some residential user equipped with a set of appliances is considered. The optimization problem is formulated as the minimization of the cost levied on the user for usage of appliances in the system. The energy consumption scheduling is determined in chronological sequence, which is obtained as a solution of an optimization problem. The schedule time period for an appliance is obtained so that as an effect on future allocated times, the optimization offers cost benefit to each user within a community in the long run. The unique features of the paper are stated as follows,

- The proposed dynamic demand response model introduces correlated equilibrium approach in a game theoretic scenario for the residential consumer.
- The proposed methodology reveals a scheduling sequence based on the users' priority order which leads to high economic benefit for a particular user as well as for society.
- The proposed model assure fairness of Nash Equilibrium among the