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A Survey of Game Theoretic Approaches in Smart Grid

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***Abstract*—The concept of smart grid to transform the age-old power grid into a smart and intelligent electric power distribution system is, currently, a hot research topic. Smart grid offers the merging of electrical power engineering technologies with network communications. Game theory has featured as an interesting technique, adopted by many researchers, to establish effective smart grid communications. The use of game theory, to date, has offered solutions to various decision making problems, ranging from distributed load management to micro storage management in smart grid. Interestingly, different researchers have different objectives or problem scopes for adopting game theory in smart grid. Nevertheless, all the game theoretic approaches for making effective smart grid solutions have a common aspect, namely the Nash equilibrium, arriving at which may lead to an optimal solution to the relevant problem. In this paper, we survey a number of game theory-based applications to solve different problems in smart grid. This survey reveals that game theory can be apparently simple yet become an effective technique to facilitate intelligent decision making in smart grid frameworks.**

***Index Terms*—Smart grid, game theory.**

I. INTRODUCTION

RECENTLY, the idea of smart grid has been gaining significant attention from research communities involving academia, industry, and government. A smart grid offers the fusion of electric power engineering technologies with network communications, through numerous power-instrumentation sensors and smart meters placed between the electricity provider and end-users. By merging these two different technologies, smart grid is expected to facilitate bi-directional communication between the consumers and the provider. With the aid of this two-way communication, power is delivered from the electricity provider to the customers. Indeed, data communications networks will play an important role in smart grid to transfer electrical power usage data from the smart meters to the data management entities. However, the smart grid data communication networks are expected to be influenced by many deciding factors, which should be taken into account, such as varying load and congestion level, power generation, changing customer demands, varying price of power, and so forth. These variable factors lead to various decision making problems. These problems are also interesting from whichever perspective we look at them. For examples, we can formulate some problems considering that the customers should receive the incentives, while other problems may focus on the benefit of the provider.

In order to make independent and inter-dependent decision making in smart grid concerned with different problems, game theory has been adopted by a number of researchers. Through game theory, researchers aim at finding optimal solutions to situations of conflict and cooperation in smart grid, under the assumption that the involved players act in their best interest. These existing research works clearly demonstrate that recently there has been renewed interest in game theory in smart grid. In the smart grid research community, game theory is emerging as a dominant formalism for studying strategic and cooperative interaction in the smart meters, consumers, and the utility provider. While the classical game theory presents a rich mathematical foundation and the concept of equilibrium in a multi-player game, it is interesting to survey its application in a complex system as smart grid. This paper will provide a survey of game theoretic developments, made so far, in smart grid.

The outline of the paper is as follows. Section II describes the considered smart grid system model. Section III presents a background to the game theory concept. Section IV provides a survey of a number of recent research works involving game theory in smart grid. We describe how the objectives and implementations of the game theory vary in these different works to solve different problems in smart grid. Section V describes challenges to using game theory in smart grid and provides concluding remarks.

II. SMART GRID MODEL

In this section, we describe the considered smart grid architecture inspired from the work in [1], [2] as depicted in Fig. 1, which has two components, namely the electric power grid and the communication network. Note that the power distribution system and communication links are considered to be separated in this smart grid framework. The power, which is generated at the primary power plant, is supplied to the consumers through the transmission and distribution substations. The transmission substation supplies power from the power plant over high voltage transmission lines (usually over 230 kilo volts) to the distribution substations, which are located at different regions. The distribution substations transform the electric power into medium voltage level, and distribute it to the building-feeders. At the building feeder, this medium voltage level is converted into a lower level, which can be used by home-appliances. From communication view point, the monitoring center communicates with the transmission and distribution substations and this is considered to be built over optical fiber technologoy since this is the most capable

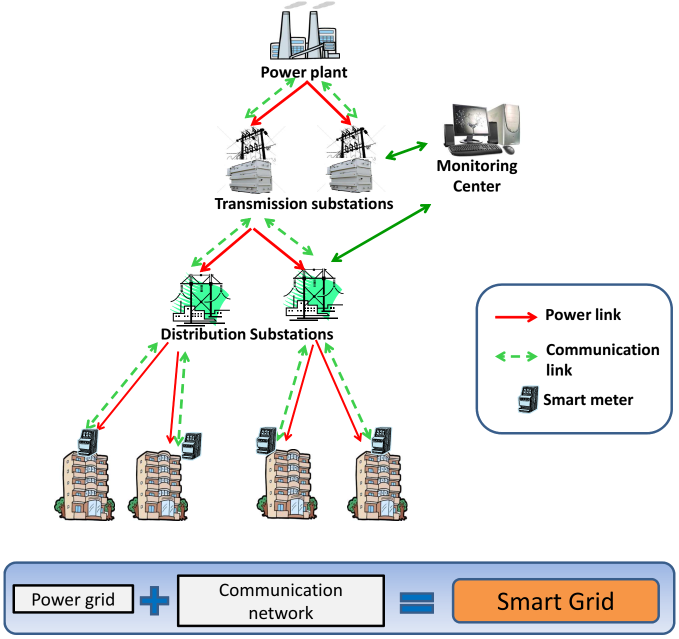

Fig. 1. Considered smart grid communications framework.

broadband technology for dealing with high volume delay-sensitive smart grid traffic. At the home users side, smart meters are installed at the building feeder that have both power and communication interfaces. Smart meters are also deployed at individual apartments or homes, which in turn can communicate with the building smart meter. The consumers can determine their consumed electric power and decide to change their consumption level by running/shutting down certain appliances (i.e., communicate with the smart grid system provider) by using these smart meters. The communication technology used in the smart meter communication is usually considered to be wireless [1]. For example, the communication between the monitoring center and buildings, and that between a building and its apartments may be facilitated over wireless broadband technologies such as 3G or WiMax. On the other hand, the home appliances communication with the home smart meter can be done through WiFi or ZigBee technologies.

As stated earlier, the objective of this paper is to describe the various game theoretic approaches proposed in literature that aim at providing effective means of communication between the home users and the utility provider based on the aforementioned system model. First, we provide a background to game theory in the next section.

III. BACKGROUND TO GAME THEORY

In this section, we present the fundamentals of the game theory. Game theory offers a popular decision making technique in economics and other engineering fields aside computer science [3]. According to game theory, the decision makers are participants or players of a game. and they are aware that their actions influence one another. A game comprises a finite set of players N, each of whom may select a stragey $s_i \in S_i$ having an objective of maximizing her utility or payoff u_i. The utility function, $u_i(s) : S \rightarrow R$ indicates every player's response to all the players' actions. Based on this concept, a game, $G = (N, A, S_i, p_{ij})$, can be modeled in which N is the set of players and A denotes the action set of the game (i.e., available resources in the game). S_i denotes the i^{th} player's strategies set and p_{ij} refers to the payoff or utility received by the i^{th} player when she chooses resource j.

The games in game theory are broadly classified into two types, namely non-cooperative and cooperative games. As the name suggests, the players in a non-cooperative game select their respective strategies without consulting or coordinating with the other players. The stragey profile $s = (s_i), i \in N = (s_1, s_2, s_3, ..., s_N)$ contains all the strategies of all the players. In contrast, in case of a cooperative game, the players attempt at reaching a consensus or agreement by collaborating with one another. In the cooperative game, the players have a choice to negotiate with others to attain the maximum possible benefit. In either games, the equilibrium strategies are selected by the players in order to maximize their individual utilities. Nash equilbrium is a game theoretic solution involving two or more players, in which no player has anything to gain by varying only her strategy in a unilateral manner. If each of the players has selected a strategy and no player can benefit by varying her stragey while others maintain their same strategy, then the current set of strategy selection and the corresponding utilities or payoffs constiute a Nash equilibrium.

In order to reach Nash equilibrium in some games, stragey profiles may be systematically ruled out. These approaches are known as iterated dominance. A pure strategy s_i is strictly dominated for the i^{th} player given there exists $s'_i \in S_i$ such that $u_i\ (s'_i, s_{-i}) > u_i(s_i, s_{-i}) \forall s_{-i} \in S_{-i}$, where s_{-i} denotes the combined strategies of all the players excluding the i^{th} player.

Also, if a players actions are not deterministic, she can make mixed strategies instead of just resorting to pure strategies. Let a mixed strategy available to the i^{th} user be denoted by m_i, and the probability that m_i is assigned to s_i is denoted by $m_i(s_i)$. Then it follows that $\sum_{s_j \in S_i} m_i(S_i) = 1$. A pure game strategy s_i, is then, a special case of a mixed strategy m_i, where $m_i(s_i) = 1$.

IV. GAME THEORY IN SMART GRID: DIFFERENT PERSPECTIVES

In this section, we provide a number of game theoretic approaches to solve a wide variety of problems in smart grid. The surveyed approaches reveal that game theory is a powerful tool, which can be exploited to reach the Nash equilibrium point and achieve different optimization goals.

A. Game Theoretic Approach to Energy Demand Estimation and Supply Cost

Most conventional demand-side management approaches for smart grid mainly focus on the interactions between a utility company and its customers or users. The work carried out by Mohsenian-Rad *et al.* [2] presents an autonomous and distributed demand-side energy management system among users based on game theory. This approach exploits the bi-directional communication framework offered by the smart meters in the smart grid architecture as shown in Fig. 1. An energy consumption scheduling game is formulated in which the users act as the players. The strategies of the players are the daily schedules of their household appliances and loads. This work assumes that the utility company can have appropriate pricing tariffs in order to differentiate the energy usage levels and durations. The work demonstrates that for a common scenario comprising a single utility company serving a number of customers, the global optimal performance in terms of minimizing the energy costs is achieved at the Nash equilibrium of the formulated energy consumption scheduling game. This distributed demand-side energy management approach needs each player to apply her best response strategy to the current total load and tariffs of the smart grid. In addition, the game ensures that the players are able to maintain privacy since they need not share their respective energy consumption schedules with others. Furthermore, the users receive incentives to take part in the energy consumption scheduling game and to subscribe to this service. The experimental results reveal that this approach is able to reduce the peak-to-average ratio of the total energy demand, the total energy costs, and also each player's individual daily electricity bills.

B. Non-cooperative Games for Smart Grid Load Balancing

In conventional energy market, the customers are expected to pay a fixed retail price for the consumed electricity. Generally, this retail pricing is changed based on the seasons or on a yearly basis. The research work in [4] argues the economic phenomenon that charging the customers a flat rate for energy consumption leads to "allocative inefficiencies". In other words, by doing so, the customers do not pay equilibrium prices as per their levels of consumption. Flat pricing, thus, leads to deadweight loss at off-peak times and excessive demand at the peak times that are not convenient for the utility provider. As a consequence, there may be short-term effects (small-scale blackouts) as well as long-term ones (excessive capacity build-up). The work in [4] presents the solution to this problem through variable-rate metering, which indicates the real-time cost of power generation in order to influence the customers to lower power consumption during the peak times. This work points out that the main challenge to implementing real-time pricing consists in the lack of cost-effective two-way smart metering for communicating the real-time prices to the customers and their consumption levels back to the utility provider. Then, this work proposes formulation of non-cooperative games among the customers with two real-time pricing schemes under more general load profiles and revenue models. In the first pricing scheme, the customers are charged a price as per the instantaneous average cost of electricity production. On the other hand, in the second pricing scheme, consumers get charged according to a time-varying version of increasing-block price. The consumer demands at the Nash equilibrium operation points are investigated. Also, two revenue models are taken into account for each of the schemes. The results indicate that both the pricing schemes contribute to similar electricity loading patterns when the customers are interested in the minimization of electricity costs alone. The work also demonstrates that the proposed formulation of the non-cooperative game belongs to the class of atomic splittable flow games. The conditions under which the increasing-block pricing scheme is preferred over the average-cost based pricing scheme is also explored through this specific game theoretic approach.

C. Game Theoretic Approach to Microgrid Modelling and Analysis

In [5], the concept of smart grid is represented as a microgrid, which encompasses a portion of an electric power distribution system below the distribution substations as shown in Fig. 1. In the microgrid game model, there is an aggregator entity (typically a company) having the responsibility of satisfying the customers' energy demand. The aggregator is considered to be able to purchase energy from the primary power plant and also the distributed generation units of the smart grid. All the distributed generation units and the customers are considered to be equipped with smart agents (i.e., smart meters) which can receive signals from the aggregator. The smart agents play the game with the aggregator with the objective of maximizing their respective revenues. Thus, in this microgrid, theer are multiple players or decision makers which interact with one another, with each striving to fulfill her goal. This particular game theory application to this multi-agent microgrid falls under the category of "dynamic games of perfect information". Dynamic games refer to the games having sequential move order. In other words, in the formulated game in this work, the players make their moves only following the action from some other player. Perfect information means that in each round of the game, the player, who is supposed to select and make the next move, has the knowledge of the moves made by other players before her. Thus, the microgrid model provides a game formulation consisting of complete information so that each player's revenue function becomes common knowledge.

D. Price-Directed Energy Utilization Using Game Theory

In [6], the notion of an Engery Internet is presented that is referred to as a more advanced implementation of smart grid in terms of quick detection of abnormal states and self-healing. The main concern addressed in the work is the lack of energy storage in the considered smart grid framework. As a consequence, focus is given toward energy anticipation and virtual buffering. This means that the customers predict their short term energy demand pattern, and accordingly place their energy demand order to the electricity provider. After the provider approves the orders, the requested energy is considered to be virtually buffered (since the actual energy has not yet been physically generated at the power plant). Thus, this work emphasizes on the fact that power generation at the power plant is adjusted to the power needs and the wasted amount of energy is, thus, reduced substantially in contrast with that in a fixed generation level. In this vein, the work presents a game to be played by the customers through their smart meters anticipation module. A game theoretic algorithm for prediction of customers energy needs are implemented at the smart meters. The smart meters use previous energy profiles of the customers to make the forecast and accordingly place the order to the utility provider. The objective of this particular game is to harmonize the power generation-demand equilibrium to establish a synergy between the anticpation of the players energy requirements and price elasticity to achieve lower peak-to-average Ratios and minimize waste of energy.

E. Agent-based Micro-Storage Management in Smart Grid

In smart grid, storage devices may be used to compensate for the variability of typical renewable electricity generation including wind, wave, and solar energy. Also, Electric Vehicles (EVs) or Plug-in Hybrid Electric Vehicles (PHEVs) may be used as additional energy storage and supplying units in smart grid. This, however, presents some challenges to the smart grid. For example, if all the individual homes (in the order of millions in a large scale smart grid) decide to store their electricity and charge their batteries at the same time, there will be a higher peak in demand in the electricity market. This would lead to potential power blackouts, infrastructure damage, and higher carbon emission to environment. To address these various issues involving storage agents in smart grid, the work in [7] presents the multi-agent systems paradigm in which multiple self-interested parties interact through smart meters. The paradigm provides a game-theoretic framework to study storage strategies that agents may adopt. Based on the normal electricity usage profile of all the users in the considered smart grid, it is then possible to compute the Nash equilibrium points, which describe when it is best for the agents to charge their batteries, use their stored electricity, or use electricity from the smart grid. Also through the proposed agent-based learning strategies, it is demonstrated how the agents would be able to learn to purchase the most profitable storage capacity. Furthermore, through evolutionary game theoretic analysis, it is also revealed that prediction can be made on the portion of the population that would actually acquire storage capacity to maximise their savings.

F. Game Theory based Demand and Load Management in Smart Grid

In [8], distributed load management scheme for the smart grid is proposed based on the capacity of the consumers to manage their own demands in order to minimize a cost function or price. From the smart grid system persepective, the overall objective is to smooth the electric demand curve and avoid overloading both the generating and distribution capacity of the grid. The system is modeled as a non-cooperative network congestion game by modelling both demand and smart grid load using a directed graph, in which the cost of a unit load over an edge depends on the total load over that edge. In other words, in the defined non-cooperative congestion game amongst the users or players, the price levels are set for the demand vector of each player. In the network congestion game, each player allocates demand as a response of other players' actions. The work demonstrates that the game formulated as such converges to a stable equilibrium point in a distributed manner. The work not only finds the local optimum points of the Nash equilbria but also shows that it is possible to arrive at a global solution to the network problem by using the equivalence between the congestion and potential games. Different user demand profiles reveal that it is possible to obtain a smoother generation curve while meeting the user demands. Furthermore, the work also exploits the smart grid network congestion games to solve the weighted demand management and the grid load management games.

V. CONCLUSION

In this paper, we presented a number of works that show the implications of game theories in the smart grid context. The surveyed work show that the versatile prospects of game theory applications to solve different interesting problems in smart grid. Future game theoretic approaches need to focus on the design of the smart grid communication protocols in order to support the distributed nature of the smart grid. Also, many of the game theory applications do not provide the global solution to the considered problem. This is also challenging in applying game theory to solve different optimization problems since the solution may remain stuck to a local minimum. In addition, the time to reach the Nash equilibrium point, in particular the global optimum, should be considered by researchers when applying game theory to solve smart grid communication problems. This is important to realize if the application is practically feasible at the smart meters since the meters have limited processing and memory resources. Thus, future endevaours involving game theoretic approaches in smart grid should take into account improved scalability and reduced signalling overhead. Also, rather than restricting to a centralized game, researchers may formulate distributed games in smart grid to improve the scalability and efficiency of the game-based solutions.

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