Game Theory Meeting
Vehicle-to-Grid Regulation: Past, Present, and Future

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Synonyms
Frequency regulation; Game theory; Vehicle-to-grid

Definition
Vehicle-to-grid (V2G) regulation services are services in which plug-in electric vehicles, such as battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), or hydrogen fuel cell electric vehicles (FCEVs), communicate with the power grid so as to provide frequency regulation services to the grid by manipulating their charging or discharging rates.

Past: Historical Background

Electric Vehicle and Vehicle-to-Grid Regulation Services
Due to the worldwide concerns on global warming, many countries have established green policies to restrain the greenhouse gas emissions, such as promoting electric vehicles (EVs). Based on the report of EV sales in 2018 (Bloomberg New Energy Finance 2018), the sales of EVs will increase from 1.1 million cars worldwide in 2017 to 11 million cars in 2025 and then toward 30 million cars in 2030 (as shown in Fig. 1) as EVs become cheaper than internal combustion engine (ICE) vehicles. The increasing penetration of EVs in transportation will not only bring environmental and economic benefits, but also help improve the reliability and stability of the power grid. Specifically, grid-connected EVs can discharge or charge their batteries to inject power to or absorb power from the grid so as to provide ancillary services to the grid. This concept is defined as the vehicle-to-grid (V2G) technique. As shown in Fig. 2, EVs charge (discharge) power from (to) the grid through a V2G unit, which includes a bidirectional inverter to enable bidirectional power exchange between EVs and the grid. With the help of smart control units, V2G unit, together with its subordinate EVs, can exchange power with the grid in response to the control signals of the grid. This enables EVs to provide ancillary services to the grid.

Among the ancillary services of the power grid, frequency regulation services are important and the most expensive ancillary services. Frequency regulation services aim to maintain the grid frequency at its nominal value through active power compensation, so as to keep real-time power balance in the power grid. Frequency regulation services include regulation-up, which
Game Theory Meeting Vehicle-to-Grid Regulation: Past, Present, and Future, Fig. 1  EV market trend

Game Theory Meeting Vehicle-to-Grid Regulation: Past, Present, and Future, Fig. 2  Vehicle-to-grid diagram

injects power from generation assets to the grid, and regulation-down, which absorbs power from the grid to loads. Some recent studies show that the bidirectional EV chargers (Kwon and Choi 2017) and power electronics inside EVs (Mer- rill et al. 2015) can compensate well for frequency regulation-down and regulation-up signals through battery charging/discharging control. Therefore, an aggregation of EVs, which constitutes a distributed energy storage system as a V2G system, can bring large capacities for providing frequency regulation services. The concept of V2G regulation services is defined to refer to the regulation services provided by a V2G system. It is able to smooth out the power fluctuations of the power grid and thus is impor-
frequency regulation signals with very limited communication between EVs and the power grid (Pham et al. 2016; Yang et al. 2013). However, since this approach only relies on the frequency regulation signals which lacks sophisticated coordination scheme of EVs, suboptimal solutions are generally yielded for V2G regulation services. For the optimization-based approach, a global optimization problem is formulated to guide the charging/discharging schedules of EVs toward the global optimum. Lin et al. (2014) proposed optimal V2G control strategies for EV aggregators based on both offline scheduling and online scheduling. Decentralized algorithms were also designed to solve the optimal V2G control problem based on the gradient projection method. To coordinate a large scale of EVs, hierarchical architectures of the V2G system are well studied in recent years (Shao et al. 2016; Chen et al. 2017). A two-level charging scheduling framework was proposed for a large population of EVs (Shao et al. 2016). In this framework, the charging schedules of EVs are coordinated by local EV aggregators, and these EV aggregators are further controlled by the grid operator. The Benders decomposition approach was applied so as to solve the hierarchical charging scheduling problem. Chen et al. (2017) proposed a general framework for hierarchical V2G system, which has no restriction on the number of levels of the system. Smart V2G aggregators are employed at different levels to facilitate the grid operator coordinating the charging/discharging behaviors of EVs. Through this approach, the computational burden of the grid operator can be tremendously reduced, and the scalability of the V2G system can be enhanced.

The aforementioned approaches are from the perspective of grid optimization and assume that EVs follow the instructions of the grid operator or aggregators. Nevertheless in the real-world operations, EVs are selfish individuals which are owned by different EV owners. These owners may be more concerned about the utilities of their EVs and the degradation issue of the EV batteries, instead of grid operations. Therefore, EVs may fail to reach an agreement with the grid because of their conflict of interests. It is thus a pressing issue on how to motivate EVs to participate into the V2G system. Game theory can provide a solution to this issue. Game theory studies how intelligent rational decision-makers act while considering the conflict and cooperation among them. Instead of following the instructions from a centralized controller, in game theory, each decision-maker makes its own actions that can maximize its utility. Applying game-theoretic approaches to V2G regulation can ensure the fulfillment of the utility of individual EV since EV can choose its optimal charging/discharging strategy to maximize its utility. Therefore, game-theoretic approaches can motivate the participation of EVs in V2G regulation. Based on the nature of the game, game-theoretic approaches can be classified as non-cooperative approach and cooperative game approach. In non-cooperative game, players are competitive and only take their own utilities as the decision goals. In contrast, in cooperative game, players collaborate with each other to some extent so as to increase their social welfare or achieve certain social goals. Some existing studies (Wu et al. 2012; Tan and Wang 2017) have already consider applying game-theoretic approaches to V2G regulation, say, using cooperative game approach (Wu et al. 2012) and non-cooperative game approach (Tan and Wang 2017). Wu et al. (2012) proposed a cooperative game-theoretic model to investigate the interaction between an aggregator and EVs in a V2G market. A backup battery bank (BBB) is also deployed in the aggregator to assure achieving the frequency regulation target. The designed interaction game is a single-level game in which EVs are players who determine their charging or discharging strategies in response to the electricity price. A decentralized coordination mechanism of EVs was designed based on game theory to achieve the optimal performance on providing frequency regulation in a distributed fashion. When considering a large V2G system in which multiple EV aggregators provide V2G regulation services, a non-cooperative two-level game-theoretic framework was proposed (Tan and Wang 2017). In the upper level, the frequency
regulation capacity bids among EV aggregators were modeled as a non-cooperative game. Based on the frequency regulation prices obtained from the non-cooperative game, in the lower level, the charging scheduling of EVs was formulated as a Markov game, in which the current move of each EV is only determined by the last moves of the other EVs instead of earlier histories of moves. It is shown that the root mean square value of frequency deviation can be reduced from 0.028 Hz to 0.009 Hz by the proposed approach.

Present: Game-Theoretic Model of Vehicle-to-Grid Regulation

Challenges

Though aforementioned work (Wu et al. 2012; Tan and Wang 2017) proposed solutions to V2G regulation using game theory, there still exist some challenges to be overcome.

- First, Tan and Wang (2017) and Wu et al. (2012) assumed that the strategy set of an individual EV only includes three states, namely, charging, idle, and discharging. This assumption oversimplifies the strategy set of EVs and thus does not consider the case that the strategy set of EVs has infinitely many elements. How to devise an infinite game in which the number of the alternatives available to each player is a continuum becomes a challenge.

- Second, Tan and Wang (2017) and Wu et al. (2012) only considered the decision-making process at each time in V2G regulation, which does not consider the time-coupling effect of the decisions. They may fail to smooth out the power fluctuations of the grid during the whole scheduling period. Therefore, how to incorporate the time-coupling effect of the decisions in the game is a challenge.

- Third, how to devise an optimal pricing scheme of the EV aggregator becomes a challenge. Tan and Wang (2017) and Wu et al. (2012) only studied the benefits of EVs and the utility grid, which fails to consider the optimal pricing scheme of the EV aggregator so as to maximize its utility.

Vehicle-to-Grid Game

To deal with the aforementioned challenges, a dynamic infinite game-theoretic model of V2G regulation is introduced (Chen and Leung 2018). The designed V2G system consists of three components, namely, the grid operator, the EV aggregator, and a fleet of EVs. The V2G system aims at providing frequency regulation services to the power grid through coordinating the charging and discharging schedules of EVs. Meanwhile, EVs are required to be charged to the desired levels. As shown in Fig. 3, the EV aggregator receives regulation request \( P_r(t) \) kW from the grid operator at time \( t \) and sets its electricity price as \( p_{EV}(t) \) per kWh. EVs then determine their charging/discharging power in response to the electricity price stipulated by the EV aggregator. Note that, due to the coupling of strategies among EVs, each individual EV also considers the charging and discharging schedules of other EVs when it makes its own schedule. Based on the charging and discharging schedules of EVs, the EV aggregator buys or sells a certain amount of energy traded with EVs, namely, \( E_g(t) \) kWh, from or to the grid operator, with the electricity price set in the power grid \( p_g(t) \) per kWh.

A dynamic infinite game is considered in which the EV aggregator and EVs plan their strategies over the scheduling period \( T = \{1, 2, ..., T\} \). The number of alternatives available to each player is a continuum. Based on the nature of the game, the interaction between the EV aggregator and EVs can be formulated as a non-cooperative game or cooperative game.

In a non-cooperative game, the interaction between the EV aggregator and competitive EVs can be formulated as a Stackelberg game, which is a two-stage strategic game in which the leading decision-maker moves first and then the following decision-makers move sequentially. In the upper level, EV aggregator acts as the leader who determines the optimal electricity trading price to maximize its own utility, based on the received regulation request. In the lower level, EVs are the followers who determine their charging/discharging strategies based on the price set by the EV aggregator. In order to motivate EVs to provide regulation services, incentives should
be given to EVs either explicitly (through paying money for EV’s regulation behavior) or implicitly (through devising pricing mechanisms so that EVs can autonomously provide regulation services while responding to the electricity price). In a cooperative game, the EV aggregator and EVs collaborate and come to an agreement to maximize their social welfare. In this sense, EV may not only concern the utility of its own but also consider the social utility (the utilities of all players) when making its strategy. The EV aggregator can give different payments to different EVs based on their behaviors in the game. Some cooperative game theories, such as Shapley value theory (Shapley et al. 1988) and potential game theory (Monderer and Shapley 1996), can be applied to analyze the interactions of players in the V2G cooperative game. Note that an underlying criteria in this cooperative game is that the utility of each player can be improved compared with the non-cooperative game. Otherwise, players will have no incentive to collaborate in this game.

**Future: Research Directions**

Based on the current studies on the V2G game, some possible directions are provided for future research.

**Hierarchical V2G Game**

In the introduced model, only the game between an EV aggregator and its subordinate EVs is considered. Nevertheless, in a large power network which includes aggregators in different levels of the system (Chen et al. 2017), hierarchical game is required to study the interaction among multiple players at different levels. Though Tan and Wang (2017) considered a two-level game in which the interactions among the grid operator, EV aggregators, and EVs were studied, the equilibrium of the game may not be reached. Therefore, it is still an open question how to validate and find the equilibrium in a general hierarchical V2G game.

**Imperfect Information Game**

To find the Nash equilibrium of the V2G game, EVs generally need to exchange their strategies or some information of their strategies with each other. In this scenario, this game is a perfect information game in which players know the strategies of other players. When we consider a scenario in which EVs are not willing to share their strategies in the game with others (due to privacy concerns), this game becomes an imperfect information game. How the players find their equilibrium strategies in the imperfect information game is a promising research direction in the V2G game.
Uncertainty in the System
In the designed game, it is assumed that all the system parameters, including the regulation requests, the arrival and departure times of EVs, and the electricity price of the grid, are deterministic when players make their strategies. Nevertheless, in practical operations of the system, there exist uncertainties in these system parameters. For instance, some EVs may depart earlier than their departure times specified at their times of arrivals due to some emergencies. Therefore, how to deal with these uncertainties in the game-theoretic model becomes a challenge. Devising a robust model for the game might be an approach to overcome this challenge.

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References