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A four-way-handshake protocol for energy forwarding networks in the smart grid

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ABSTRACT

Distributed mobile energy storage (DMES) units, which have been recently available in the form of Plug-in Electric Vehicle (PEV) batteries, provide unique opportunities to enhance the efficiency of the smart grid. On the other hand, without communications, uncoordinated supply may risk the stability of the grid, while mobility and variable availability of the batteries make the planning task challenging for the utilities. In this paper, we propose a four-way handshake protocol and a token-based energy forwarding network model for the electricity distribution system that allows energy to be supplied in a store-and-forward fashion similar to packet delivery in delay-tolerant networks. Based on this model, we develop a novel vehicle-to-grid power flow coordination approach, where the power acquired by the delay-tolerant loads is aggregated into tokens which are then matched with the available capacity of the PEV batteries. Energy transactions between delay-tolerant loads and PEVs rely on their communications with the energy management system at the distribution level. Our four-way handshake protocol assures tokens coming from loads and grants coming from storage are matched properly at the distribution level. Our approach provides a convenient supply for loads via PEV batteries while addressing the mobility of vehicles and preserving fairness. We provide a mathematical analysis of the proposed approach and conduct simulations showing that the proposed protocol is able to provide fair access opportunity to PEV owners. Furthermore, by introducing the queuing theory perspective, we enhance the planning capabilities of utilities.

1. Introduction

Communication technologies and protocols will play the fundamental role in transforming the distribution of electricity. Communication between loads and suppliers, whether it be a large scale generator or a battery of an electric vehicle, open up new venues that allow energy to be stored and forwarded locally. Energy forwarding concept is rather novel and it calls for protocols to facilitate coordination between distributed mobile storage and delay-tolerant loads.

In fact, emerging energy storage technologies such as lithium-ion batteries, fuel cells, advanced ultra-capacitors and their intelligent integration to the electricity grid can provide numerous opportunities to enhance the efficiency of the smart grid. Among many novel storage technologies, Plug-in Electric Vehicle (PEV) batteries have a unique position as they are both distributed and mobile. PEV batteries are closer to loads than utility-owned generators and storage, thus they can reduce the line loss factor associated

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with distance. Furthermore, they can help to increase the penetration level of renewable energy generators. For instance, according to the research in [1], PEV batteries can improve the dispatchability of the renewable resources and reduced their cost by compensating for prediction errors, since inaccurate predictions are significant factors that increase the cost of electricity [2]. Note that, we use the term "distributed mobile energy storage" interchangeably with PEV batteries. The ideas proposed in this paper can be generalized to any distributed and mobile storage technology that may become available in the future.

Despite the abovementioned opportunities and the fact that electrification of transportation can reduce vehicle emissions, the interaction of PEVs with the smart grid bares many open problems [3]. Especially the distribution system is anticipated to experience overloading if multiple PEVs are simultaneously charged in an uncoordinated manner [4]. Various studies have addressed the PEV charging problem by proposing control and coordination oriented approaches [5–11]. Similar to charging, discharging from PEV batteries, which is also known as vehicle-to-grid (V2G) power flow, also requires coordination. Uncoordinated power flow from multiple greedy vehicles may generate surplus power and risk the stability of the grid. At one hand, PEV supply may cause an imbalance in supply and demand, and cause the frequency of the grid divert from 60 Hz significantly, at the other hand, distribution system limitations may be exceeded with uncontrolled surplus power.

Recently, implementing V2G in the smart grid has been discussed in several studies. In [12], the authors have formulated V2G power flow as a unit commitment problem assuming that a large number of PEVs are available under the contract of a utility. Han et al. [13–15] have addressed the complexity of controlling individual PEVs and proposed employing an aggregator to provide regulation services. Regulation service basically aims to maintain the grid frequency as close as possible to the nominal value where the regulation service providers are contracted to absorb power when the frequency increases, i.e. in case of surplus power, and supply power when the frequency drops below the nominal value. Utilizing PEVs for regulation services has been also considered by Wu et al. where the authors have proposed a game-theoretic approach to model the interaction among independent vehicle batteries and an aggregator [16].

In the literature, V2G concept has been generally considered for frequency regulation, and most of the studies have assumed that PEVs are operated under contracts imposing constraints over either available capacity, time to plug-in, time to stay online or the time to disconnect. These conditions may sometimes be hard to meet since the primary purpose of a PEV is driving. For instance, if a PEV has been driven for more miles than the regular driving pattern or if the battery has not been charged due to price related concerns, then it might not be available for discharging. Similarly, if the battery is fully charged then it will not be available for absorbing the surplus power that may be required for regulation. Furthermore, maximizing revenues will be the primary objective of PEV owners for selling electricity to the grid and preserving fairness among PEVs has not been addressed in the literature.

In this paper, we propose a four-way handshake protocol to address the integration of distributed mobile energy storage units to the smart grid in a flexible manner. We further use a queuing theory perspective to study the performance of the proposed framework. Our approach provides valuable insights to the V2G power flow coordination problem where multiple-class solution was proposed in [17]. We are motivated by the token network idea of [18] where the authors have studied energy routing from renewable generators to depleting storage units. More recently Gelenbe proposed Energy Packet Networks (EPN) for on-demand energy provisioning for the cloud [19]. In this paper, we assume load and storage related information is available at the energy management module of the distribution system through one of the existing smart grid communication technologies such as Power Line Communications (PLC) and WiFi [20,21]. We consider a distribution system where delay-tolerant demands are aggregated in fixed size tokens, and a PEV is allowed to sell power only if it allocates a token. This corresponds to energy forwarding since vehicle batteries work in store-and-forward fashion and a handshake protocol is designed to allow vehicles and loads to be coordinated. Each PEV is allowed to allocate one token at a time and if there is no token available, the PEVs are queued. Using a token for each transaction allows more PEVs to access the system and aims to avoid greedy behavior. If a PEV is willing to sell more power than the size of a token, it is pushed at the end of the queue allowing for others to make revenues too. We provide analysis for blocking probability, queue length and waiting time which are significant parameters affecting the planning decisions of utilities, as well as decisions of individual PEV owners. We show by analysis and simulations, that our approach is able to provide supply using PEV batteries while avoiding the greedy PEVs risking the grid stability. Furthermore, our approach preserves fairness among PEVs.

Our contributions can be summarized as follows.

- A four-way handshake protocol between the vehicles and the loads is introduced.
- Vehicle-to-grid power flow coordination is modeled from a queuing theory perspective, and the distribution system is formalized as a token based system for the first time.
- The proposed approach ensures that greedy PEVs, those are willing to make more revenues, do not risk the stability of the grid.
- The proposed approach is more flexible than the existing V2G studies and can handle the inherent mobility and variable availability of vehicle batteries.

The rest of the paper is organized as follows. In Section 2 we briefly summarize the studies focusing on the integration of PEVs to the smart grid. In Section 3 we present the system model, define the problem and present our approach in detail. In Section 4, we provide the mathematical analysis of the proposed approach. Section 5 provides the numerical results of our analysis and simulations.