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Strategic charging method for plugged in hybrid electric vehicles in smart grids; a game theoretic approach

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ABSTRACT

Implementation of various incentive-based and time-based load management strategies has great potential to decrease peak load growth and customer electricity bill cost. In recent years, developments in Plug in Hybrid Electric Vehicles (PHEVs) have provided various environmental and economic advantages. However, high penetration of electric vehicles in to the grid may cause high peak loads at different times of the days. Using advanced metering and automatic chargers makes it possible to optimize the charging cost, and release generation capacities to provide sustainable electricity supply. Using an appropriate encouraging program is a simple way for vehicle owners to manage their energy consumption and shift the time of charging to proper time of the day; and therefore, to reduce their electricity bill. With these objectives, this paper proposes a new practical PHEVs' charging scheduling programs aiming at optimizing customers charging cost by considering the generation capacity limitation and dynamic electricity price in different time slots of a day. Using a stochastic model for start time of charging and the duration of it in the proposed optimization algorithm, make this method a practical tool for modeling the vehicle owners' charging behavior with the purpose of peak load shaving.

1. Introduction

Plug in Hybrid Electric Vehicles (PHEVs) use novel technologies with the main purpose of decreasing dependence on fossil fuels. These vehicles use batteries to power an electric motor and use another fuel, such as gasoline or diesel, to power an internal combustion engine. In fact, these vehicles are the combination of electric and fossil fuels vehicles, and one might consider a PHEV if an all-electric vehicle (EVs) cannot meet all of his driving needs [1]. These electric cars are also the most efficient replacement in favor of conventional cars due to various reasons from environmental issues to economic aspects described as follows.

Firstly, greenhouse gases (GHGs) emission from conventional cars is one of the major factors contributing to moving toward EVs and PHEVs [2]. By considering the fact that the transport sectors have a significant role in the total GHGs emissions (e.g. about 17% of total U.S. GHG emissions [3]), enhancing and optimizing the use of clean energies in the transportation sectors can be effective in decreasing the existing GHGs emissions. Hence, governments are making an attempt to shifting transport system to modes with naturally low-carbon emission; and consequently, expand electric green vehicles such as EVs and PHEVs with the aim of reducing the harmful environmental impact of fossil fuels [4]. For PHEVs, CO_2 reduction levels will depend on the proportion of miles driven using battery electricity and petroleum consumption. However, in countries where average driving distances per day are relatively short, a higher percentage of driving distance is expected to be covered by battery power; and thus, PHEVs can play an important role in decreasing the GHGs emission in these areas [5].

The next factor is oil depletion that causes increasing in oil prices, and makes it more economically to use a substitute source of energy in vehicles and transportations [6]. Considering this fact, various vehicle industries around the world have announced plans to begin serious production of vehicles that use electricity, solar power, steam, ethanol, liquid nitrogen or hydrogen instead of fossil fuels [7]. PHEVs as the most attractive replacement are expected to use about 40–60% less petroleum than conventional vehicles; hence, they reduce our dependence on oil. As a result, it is predicted that these new types of vehicles will comprise over 15% of total vehicles until 2020 [8].

Another main reason accounting for growing interest in PHEVs is their lower operating cost and higher efficiency because of their simple motor structure, and using electricity as fuel [4,6]. PHEVs will likely cost \$1000–\$7000 more than comparable non-plug-in hybrids; however, fuel will cost less since electricity is much cheaper than gasoline, and it can be expected that fuel savings will offset the vehicle cost when the customer uses PHEVs. Furthermore, currently in United States, federal tax incentives are currently available for qualifying PHEVs [9].

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PHEVs also provide electric-powered travel, and have ranges comparable with conventional vehicles because they can operate as both EVs and conventional vehicles. The vehicle's battery can be recharged at electrical outlets, hence PHEVs substitute electricity for gasoline to supply a portion of the power needed for travel [10,11]. These vehicles have a large battery that is charged from plugging into a standard 220V/13A electricity outlet for a few hours each day. Additionally, large efficient batteries are now available for supplying the vehicle's needs for urban driving. Driving range supported by each full battery charging is about 70 km, which is suitable for short journeys in cities [12].

According to these reasons PHEVs' industries have been growing at a high pace in recent years, and are considered to have a great potential as replacement of conventional vehicles. However, the introduction of PHEVs into the marketplace presents several new infrastructure challenges, which will affect most industry stakeholders to some degree [12–14]. While a smart grid may not be essential to PHEVs operation in the near term, the availability of sensors and control systems to manage PHEVs charging and discharging, and infrastructure to support interconnection at locations throughout the grid, would eventually allow utilities and vehicle owners to maximize the benefits of PHEV technology [15]. Recently developed smart meters and charging software make it possible to monitor electricity flows between batteries and the grid and reschedule charging to times outside high demand times [16,17]. The methodology used to establish PHEV charging parameters, including charge power, charge energy, and charge times, began with an evaluation of typical daily vehicle trips and daily vehicle miles traveled based on data from the 2009 National Household Survey [18]. Additionally, an evaluation of actual PHEV driver behavior and an evaluation of charge power requirements (based on experience with charge characteristics of various battery chemistries) were conducted. Upon conducting these evaluations, it was concluded that 40 miles of charge depleting range is necessary for an average PHEV if no infrastructure is available outside of the owner's primary residence. It is, therefore, considered important to evaluate charging infrastructure in both residential and commercial settings because the availability of a rich charging infrastructure can reduce the peak load caused by charging in different hours of the day or night [17].

Plug in hybrid vehicles literature may be categorized in three groups. Area under discussion in the first group [19–23] was the PHEVs impacts on power grids. Prominent subjects discussed in these studies include: Determining the optimal places of PHEVs' parking lots which provide vehicle to grid (V2G) power as distribution generation [19], Modeling microgrids system with PHEVs and designing appropriate controllers for frequency stabilization [20], Introducing PHEV-load tool to determine the optimal charge and discharge of the PHEVs fleet and replacing conventional peak reserve capacity with PHEVs [21], Determining the optimal charging profile to enhance the power grid operational condition such as reducing power loss and increasing load factor [22], and utilizing an optimization algorithm to maximize the advantages of using EVs' batteries as energy storage systems in power grids [23].

The second category [24–27], deals with the PHEVs' batteries impact on charging behavior. The main subjects of these studies are: Determining optimal charging strategies based on battery power loss model to minimize charging cost [24], optimizing charging behavior to maximize the battery life time and energy trading profits [25], deriving an optimization mechanism for charging pattern of PHEVs to simultaneously minimize the total cost of fuel and electricity and the total battery health degradation [26], investigating charging scheduling by approximating batteries behavior (linear and quadratic approximation) [27].

The final group addressed the various charging strategies and designing optimization algorithm to achieve appropriate charging profile [28–34]. The major subjects examined in these studies are: Designing energy management strategies for fuel cell/batteries/ultra-capacitors hybrid vehicles [28], Designing smart load management control strategy for coordinating PEV charging based on peak demand shaving, improving voltage profile and minimizing power losses [29], Proposing PHEV charging mechanism for peak load management on context of time-of-used(TOU) electricity price market [30], Designing demand side management strategy under real time pricing [31], Using sensor web services for management PHEV charging in order to increase the administration ability of the utility over load and increase the control of the consumer on her energy expenses [32], proposes an operational framework for multiple PHEV charging stations based on a multi-queue system to minimize the waiting time of customers and to determine an optimal PHEV allocation [33], Investigating the role of electric vehicles in an electricity network with a high contribution from variable generation such as wind power by using stochastic trip generation profile to generate realistic journey characteristics, whilst a market pricing model [34].

Although these above-mentioned studies have examined various aspects for PHEVs charging scheduling, it is imperative to propose a comprehensive and less complex algorithm that is applicable to power market which considers dynamic pricing. In this paper, the PHEVs' charging scheduling problem is revisited and a time-based Demand Response (DR) program is developed which aims at near optimum scheduling by taking into consideration vehicle owners charging behavior, dynamic electricity prices. The method proposed in current paper tries to address these shortcomings over most of the earlier works cited in this literature, in the sense that it considers the PHEV owners to be price anticipator which means that they are willing to minimize their cost of charging according to the electricity price in each time slot. Besides, the PHEV charging is seen as a game among all car owners, the purpose of which is to minimize all car owners' cost of charging. This model is based on probabilistic model of customers' behavior which is more accurate in practical applications. This algorithm can be used by utilities to encourage customers to use their smart chargers in order to shift their charging to the periods that electricity supply is more economical.

The rest of the paper is organized as follows: In Section 2 the objective function of the optimization problem for PHEV charging game is introduced. Section 3 contains description of the proposed scheduling program and its respective optimization technique. In Section 4 outputs of the technique are illustrated by simulation, and in Section 5 the paper is concluded.

2. PHEV charging game

This section introduces modified PHEV charging pattern between a numbers of drivers that result in near optimum electricity cost. In the first step, it shows how each customer charging decision affects other customers' bill cost. Then, in the next step, a specific decision making algorithm will be developed for each customer to charge its electric vehicle in the time duration which result in minimum cost for him and other customers simultaneously.

Step(1). Cost Calculation: Assume there are N PHEVs that are going to be charged only in a specific period $[a, b]$ during night (for example from 10 pm to 7 am). This assumption does not affect the generality of the proposed algorithm and can be varied based on the case study.

The charge needed for each vehicle is calculated according to the following equation:

$$C_{n,i} = C_{max,i} - C_{a,i} \quad (1)$$

In which: $C_{n,i}$ the needed charge for PHEVi, $C_{a,i}$ the available charge capacity when vehicle i arrives home, and $C_{max,i}$ the maximum