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Optimal vehicle to grid planning and scheduling using double layer multi-objective algorithm

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ABSTRACT

Vehicle to grid is a revolutionary technology that allows energy exchange between electric vehicles and power grid for mutual advantages. The implementation of appropriate vehicle to grid energy management system can maximize the potential of electric vehicles to provide grid ancillary services. This paper proposes an optimal vehicle to grid planning and scheduling by utilizing a novel double layer multi-objective algorithm. This optimization algorithm utilizes the grid-connected electric vehicles to perform peak load shaving and load levelling services to minimize the power grid load variance in the first layer optimization. Meanwhile, the second layer optimization minimizes the reactive power compensation for grid voltage regulation and therefore, optimizes the vehicle to grid charger's capacitor sizing. The second layer optimization algorithm utilizes an approximated formula from the simulation of a vehicle to grid charger. The proposed vehicle to grid optimization algorithm considers various power grid and electric vehicle constraints for practicality purpose. With the real time implementation of the proposed algorithm, the optimization results show that the power load curve is effectively followed the preset constant target loading, while the grid voltage is successfully regulated to the predetermined voltage level with minimal amount of reactive power supply from the optimal charger's capacitor.

1. Introduction

In recent years, the deployment of electric vehicle (EV) has become the catalyst in reducing the impact due to climate change, by alleviating carbon emissions of roadway vehicles. The optimization model and analysis has been proposed to determine the best combination of vehicle types to achieve minimal emissions with the lowest investment [1]. It is envisaged that the key findings from the optimization model and analysis shall assist the policy makers and transportation planners to prepare the transportation framework and structure to accommodate future influx of EV [2]. On the other hand, EVs may not be environmental-friendly if EV batteries are charged from the power grid with fossil fuel generation. Despite the contradiction, authors in Ref. [3] have concluded that electrification of roadway transportation is able to reduce fuel consumption and emissions without renewable energy integration. Obviously, the fuel consumption and emissions will be further reduced if renewable energy generations are widely adopted. EVs powered by hybrid solar system can also enhance the reduction of greenhouse gases [4].

The benefits and challenges of EV deployment on the environment, economic and power grid have been reviewed in Ref. [5]. Despite the environmental and economical benefits, EV deployment has brought negative impacts to the power grid as a consequence of EV charging operation. The impact assessment of EV charging to the Swiss distribution grid has been investigated in Ref. [6], where the study indicates that many substations will be overloaded if the EV penetration level is more than 50%. The additional EV charging loads become the bottlenecks where capacity investment is required to solve the overloading problem. The authors in Ref. [7] have examined the power quality impacts of EV charging to the power grid and conclude that the Level 1 EV charging increases the neutral-to-earth voltages which can lead to stray voltage incidents. The authors in Ref. [8] have revealed major impacts of EV charging to the power grid, such as overloading of grid components, voltage drop, harmonics and power loss problems.

Nevertheless, a new opportunity has emerged due to the interaction between EVs and power grid, which is known as vehicle

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Nomenclature

ΔP	grid load variance
n	EV index, $n = 1,2,\ldots,80$
N	maximum EV index
t	time index, $t = 1,2, \ldots,24$
A_n	availability of nth EV
D_n	battery degradation coefficient of$n$th EV
K_n	optimal numbers of EV for V2G application
P_{EV}	total power of EV loads/sources
$P_{\mathrm{EV,charging}}$	EV charging rate
$P_{\mathrm{EV,discharging}}$	EV discharging rate
$P_{\mathrm{EV,max}}$	maximum EV power exchange rate
P_{flow}	active power flow from grid to EV system and loads
P_{grid}	generated power from generation plants
P_{load}	power grid existing loads
P_{target}	target loading
Q_{flow}	reactive power flow from grid to EV system
SOC_n	battery SOC of nth EV
$SOC_{n,max}$	maximum SOC of EV battery
$SOC_{n,min}$	minimum SOC of EV battery
V_{grid}	power grid voltage
$V_{\mathrm{grid,max}}$	maximum limit for power grid voltage
$V_{\mathrm{grid,min}}$	minimum limit for power grid voltage
$V_{\mathrm{regulated}}$	regulated power grid voltage
x	active power coefficient
y	grid voltage coefficient
z	constant coefficient

to grid (V2G) technology. The functional principle of V2G technology is that an EV can act as a mobile energy source other than as a charging load. Hence, V2G technology allows bidirectional energy exchange between EV batteries and power grid for shared advantages, such as ancillary services, active power support and reactive power compensation for power grid whilst revenue benefits for EV owners [9]. There are many V2G studies highlighted in the literature which can be further classified into two categories: (1) the development of smart bidirectional V2G charging station and (2) the implementation of V2G scheduling.

The former research category is well established since it is the initial requirement to realize the V2G technology. Several studies have discussed the development of bidirectional V2G chargers with decoupled real and reactive power control [10]. The proposed control can manage the real power flow for EV battery charging and discharging processes without affecting the reactive power, which is usually set at zero value to achieve unity power factor operation for V2G charger [11]. Meanwhile, reactive power compensation control is adopted in the EV charger proposed in Ref. [12] to regulate the grid voltage utilizing the bidirectional reactive power flow between power grid and EV charger. Similarly, the authors in Ref. [13] have proposed a reduced-capacity V2G charger to provide reactive power support to the power grid. The utilizations of both real and reactive power controls are essential to develop a feasible bidirectional V2G charger.

Optimal V2G management systems are utilized to schedule the charging and discharging operations of a large fleet of EVs to achieve specific objectives. The authors in Ref. [14] have employed the V2G scheduling of electric buses and battery electric transit to reduce electricity generation related carbon emissions. Meanwhile, the authors in Ref. [15] have proposed an optimal V2G dispatch model to achieve the similar objective. Several studies have proposed the optimal V2G scheduling to accomplish profit maximization and cost minimization. A simultaneous scheduling of combined energy exchange modes has been proposed in Ref. [16] to optimize the incentives for both V2G aggregator and EV owners. Optimal V2G scheduling in a renewable micro-grid is presented in Ref. [17] to minimize the operation cost. Furthermore, multi-objective V2G scheduling have also been proposed in the literature. The authors in Ref. [18] have presented a multi-objective resource scheduling for V2G system which focuses on the reduction of power system operation cost and air pollutant emissions. Similar studies have been presented in Refs. [19] and [20], which utilize the V2G technology to achieve maximization of net revenue and emissions savings with the consideration of various uncertainties.

Energy management of large scale EV fleets can be employed to maintain the power grid reliability. In Ref. [21], an optimal-based V2G model has successfully performed the power grid load shifting to flatten the power load curve. Furthermore, a study in Ref. [22] has developed a coordinated control strategy that utilizes a large scale of EVs to achieve power grid frequency regulation and support the renewable energy generation. In addition, a V2G control strategy for power grid spinning reserve service is presented in Ref. [23]. The results reveal that the proposed V2G control strategy significantly decreases the system cost and increases the system capability of integrating with variable renewable sources. Moreover, system loss reduction by V2G technology has attained the attention of many researchers. The authors in Ref. [24] have proposed an optimal EV charging strategy using particle swarm optimization, which can reduce power grid losses. Meanwhile, research in Ref. [25] has achieved power loss reduction and voltage improvement while considering real life practical constraints. The V2G scheduling of active and reactive resources is utilized in Ref. [26] to obtain the best solution from the technical and economical perspectives. On the other hand, the authors in Ref. [27] have presented a multi-objective optimization on the global level to manage the integrated EVs to serve as energy storages for the renewable energy generation.

Despite the increasing literature on the aforementioned V2G research topics, there is rather limited literature which combines both bidirectional V2G charging station and optimal V2G scheduling. In the context of V2G scheduling, all the public, residential and commercial V2G chargers are usually assumed to have enough capability to support the dual power exchange for the large scale V2G application. Inappropriate capacity planning of the V2G charger can limit the performance of the practical V2G system. For instance, improper DC-link capacitor sizing of the V2G charger will not provide sufficient reactive power support to the V2G system for grid voltage regulation. Therefore, proper DC-link capacitor sizing by using optimal V2G scheduling can fulfill the research gap to further enhance the V2G potential with minimal investment.

This paper proposes an optimal V2G planning and scheduling using double layer multi-objective algorithm. The main contributions of this paper are: (1) to highlight comprehensive planning procedures for V2G chargers using optimal V2G scheduling, (2) to present a double layer multi-objective V2G optimization algorithm for grid load variance minimization and grid voltage regulation, (3) to optimize the DC-link capacitor sizing of the bidirectional V2G charger, and (4) to demonstrate real time V2G scheduling for a large EV fleets. The rest of the paper is organized into several sections. Section 2 reveals the planning procedures for the V2G chargers