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A novel real-time scheduling strategy with near-linear complexity for integrating large-scale electric vehicles into smart grid

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HIGHLIGHTS

- A novel real-time scheduling strategy for integrating large-scale electric vehicles (EVs) into smart grid is proposed.
- The conceptual framework and the major challenges for real-time EV scheduling are discussed.
- The proposed strategy can tackle the uncertainty arising from the stochastic EV connection.
- The proposed strategy can alleviate the elevated peak loads arising from EV charging significantly and efficiently.

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ABSTRACT

Coordinated charging can utilize the properties of electric vehicles (EVs) to obtain various benefits. However, there are two major challenges, viz. the uncertainty of EV charging behaviors and the overlong solving time for the optimal solutions in the charging scheduling problem of large-scale EVs. It is almost infeasible to precisely predict the charging information of EVs due to the uncertainty of their mobility as transportation tools. In order to tackle this issue, the real-time charging scheduling method is employed in this paper. Even so, the computational complexity is crucially important in the real-time scheduling methods since the charging strategies of large-scale EVs must be acquired in a short time. Hence, a high efficient methodology is proposed for EV real-time scheduling based on the definition of capacity margin index and charging priority index. Finally, the simulation results show that the proposed scheduling method has a significant superiority over the uncoordinated charging in the regard of relieving the demand stress on the power system. Moreover, the complexity analysis demonstrates that the proposed method has near-linear complexity so that it can acquire the optimal real-time charging scheme in a rather shorter time than other methods.

1. Introduction

The traditional transportation highly depends on fossil fuels in most countries of the world. In a populous nation like China, the sustainable development of transportation sector has become more urgent to be considered than ever before. Statistics released by Chinese Transportation Bureau found there are 194 million cars and 310 million automobilists in China by 2016; furthermore, China has added 27.5 million cars and 33.1 million automobilists in 2016, both hit all-time highs. Apparently, the extraordinary growth of the car ownership has brought serious challenges on both environment protection and energy security in China. As a result, Chinese government has regarded electric vehicles (EVs) as one of the effective approaches to reduce the emissions of harmful gases and relieve the dependence on fossil fuels. With all kinds of strong incentive policies released by Chinese central government, the number of EVs in China is expected to reach 5 million by 2020. Nevertheless, the uncoordinated charging behaviors of large-scale EVs will cause significant negative impacts on the existing power systems, such as the elevated load peaks, the increased energy losses, the power quality degradation and so on [1–5]. Moreover, it will explicitly increase the risk of substation overloads [6]. As we all know, the expansion of the power grid will take a huge cost of transformation, and is not easy to achieve in the short term. Correspondingly, the coordination of EV charging is proposed to maintain the stability of power grid by means of achieving the balance between supply and demand of electricity [7]. In general, the scheduling approaches for EV

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coordinated charging are divided into two categories according to the scheduling time horizon: EV day-ahead charging scheduling and EV real-time charging scheduling [8–10].

Substantial algorithms have been developed on the day-ahead charging scheduling strategies for the EV aggregator. In most cases, the charging tasks of EVs are managed by an EV aggregator in a coordinated way. In the day-ahead energy market, the EV aggregator should make bidding decisions for the day ahead based on the historical data. Once the bidding strategy is confirmed, the bidding instruction must be communicated to the Distribution System Operator (DSO) for prior approval. Then, the DSO will check whether the bid strategy will be the safe operation for the distribution grid, and negotiate with the EV aggregator until a bidding agreement is achieved. Obviously, the required information about EV availability and consumption is the key to obtain the optimal bidding strategies in a day-ahead time horizon. All these methods presented in [11–16] are built on the assumption that the EV aggregator has full knowledge of the EV variables involved in the optimization model. However, this assumption is not impractical due to the uncertainty of EVs' trips. In order to handle the uncertainty on EVs for mobility, a practical deterministic approach is presented with the ability to be resilient to uncertain data [17]. Statistical forecasting methods are also developed with regard to the EV variables, and the gap in the optimal results caused by the forecast error in the EV information forecasting model is studied in [18]. Moreover, the optimization model presented in [19] is revised and enhanced to reduce the gap. In addition to the forecasting methods, the stochastic optimization model is proposed to amend inevitable deviations between day-ahead bids and actual real-time energy purchases so as to deal with the uncertain nature of fleet characteristics [20]. However, this method should belong to real-time charging scheduling approaches. Generally speaking, the major problem in the day-ahead charging scheduling approaches lies in the uncertainty of EVs' charging behaviors. And, the unavailability of EVs' charging information will lead to huge troubles in day-ahead scheduling manipulation.

Given the above, the real-time scheduling methods are developed to achieve the practical application in energy management with the consideration of a stochastic EVs' driving scheduling [21–24]. In the real-time centralized controlled approaches, the main functionality of EV aggregators is to collect the EV charging information, optimize the charging scheduling strategy and transmit the charging instructions to the charging posts. The whole process must be executed in several minutes or shorter periods to ensure the implementation of coordinated charging regardless of the population size of EVs [25]. The rapid communication between EV aggregators and the charging posts is easily realized in the modern technological level. It can be observed that the solving time becomes critical to obtain the real-time solutions for large-scale EVs.

Substantial research exists regarding the electricity price mechanism to handle the charging problem of large-scale EVs. The real-time time-of-use (TOU) price mechanism is proposed to motivate EV owners to make their autonomous charging choices for the cost minimization [26–29]. Although the computational burden is distributed to each EV, the price incentives cannot provide more optimal solutions for EV coordinated charging than centralized controlled approaches due to the individual charging autonomy of EVs. With a long-term view, the centralized controlled approach is a superior alternative for improving the energy utilization especially with the integration of renewable energy including wind and solar energy.

However, centralized controlled approaches must tackle the problem in computational complexity when a large population of EVs involved. The objective functions are adopted in centralized approaches such as minimizing power losses, minimizing load variances, minimizing generation costs, maximizing aggregator profits and so on [21,24,30–33]. These optimization models belong to either quadratic programming or integer programming. As a consequence, it will cost an unacceptably long time to acquire the optimal solutions when high penetration rates of EVs involved. The linear programming models as convex optimizations are proposed in [34–36] to reduce the complexity; however, the computational complexity is still rather high. In addition, the methods presented in [37,38] have to give up the global optimal solutions and turn to local optimal solutions [37] or satisfactory solutions [38] so as to reduce the execution time. Furthermore, the fast computation algorithms such as the interior point method [39], genetic algorithm [40] and particle swarm optimization (PSO) algorithm [41] are applied to accelerate the solving process. Although the reduction of the execution time is achieved to some extent by these methods, the solving time still grows non-linearly along with the EV variables. As a result, the essential problem for real-time optimal solutions is to establish an optimization model with low computational complexity when a vast amount of EVs involved.

Generally, there are two major challenges, viz. the uncertainty of EVs' charging behaviors and the overlong solving time for the optimal solutions in the charging scheduling problem of large-scale EVs. In the day-ahead charging scheduling, the EV aggregator has enough time to make bidding decisions; however, it is almost infeasible to precisely predict the charging demands of EVs for the day ahead due to the uncertainty of EVs' mobility as transportation tools. Worse still, a failed biding will lead to the risk of threatening the stability and security of power grid [42]. Hence, the real-time scheduling approach is employed in this paper for EV coordinated charging. In previous work, the majority of proposed models are not applied to optimize the real-time charging strategies of large-scale controlled EVs [24,43–47]. Thus, the analysis about the solving time of the proposed methods is ignored since only a small amount of EVs is taken into account. It has been demonstrated that the solving time is determined by the computational complexity of the established algorithm [48]. The computational complexity of the existing methods is rather high that it becomes difficult to acquire the real-time charging strategies of large-scale EVs. Therefore, it is necessary to develop a rather low complexity algorithm when a large population of EVs involved in real-time charging scheduling.

In this paper, a near-linear complexity real-time scheduling strategy is proposed to integrate large-scale electric vehicles into smart grid. Firstly, the real-time scheduling idea is adopted to make EV coordinated charging into practical applications. Then, a future conceptual framework is developed to implement EV real-time charging scheduling. Additionally, in consideration of the computational efficiency for the real-time solutions of large-scale EVs, a near-linear complexity algorithm is constructed based on the definition of the capacity margin index and charging priority index. At last, from the perspective of computational complexity, the solving time by the proposed method is growing near-linearly with the number of EVs involved, which is more efficient than other controlled methods.

The rest of this paper is organized as follows. Section 2 describes the real-time scheduling conceptual framework and the major existing challenges for its practical implementation. Then, the proposed optimization model is presented based on the definition of capacity margin index and charging priority index in Section 3. Next, Section 4 introduces the implementation background in Shenzhen in 2035 and simulates the input data to prepare for the proposed methodology. After that, simulation results by the proposed methodology for different number of EVs involved are discussed, and the complexity analysis is given to show the high efficiency of the proposed model in Section 5. Finally, Section 6 concludes our work and points out the future scope.

2. Problem statement

2.1. Description of EV real-time charging scheduling

Due to the mobility characteristics of EVs, a high degree of uncertainty exists related to when and where EVs charge. Moreover, this will result in an extremely headache problem in the day-ahead charging