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Multi-objective optimal charging of plug-in electric vehicles in unbalanced distribution networks

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ABSTRACT

Plug-in electric vehicles (PEVs) as new generations of transportation systems have recently become a promising solution to mitigate emissions of greenhouse gases produced by petroleum-based vehicles. Existing power systems may face serious reliability and power quality problems in supplying emerging PEV charging loads unless the charging task is coordinated. In addition, in real world applications, most PEVs are single-phase loads supposed to be charged from residential or commercial outlets. In this paper, a multi-objective optimization framework is proposed to optimally coordinate the charging of single-phase PEVs with dynamic behavior in unbalanced three-phase distribution systems employing smart grid facilities. Objective functions include total cost of purchasing energy in a multi-tariff pricing environment as well as grid total energy losses over charging span. The objective functions are optimized subject to network security, power quality, and PEV constraints. Fuzzy memberships are used to transform differently-scaled objective functions into a same range in order to ensure the Pareto optimality of the multi-objective solution. The proposed method is tested on an unbalanced three-phase distribution system and obtained results, which are discussed in detail, confirm its efficiency in getting a solution satisfying both objective functions as well as in the speed.

Introduction

Plug-in electric vehicles (PEVs) have recently become a promising substitute for traditional petroleum-based vehicles to alleviate increasing emissions of greenhouse gases and their consequences such as poor air quality and climate changes. It is anticipated that PEV utilization, which is more intensified nowadays by increasing oil prices, becomes very popular in near future [1] because of their diverse advantages such as high efficiency in energy conversion, less operating cost, and lower carbon emissions. However, in spite of fascinating features of PEVs, their uncoordinated charging can adversely impact the reliability and power quality of electricity networks and can also lead to deteriorating existing load peaks or even creating new load peaks [2]. In fact, the problem of how to incorporate emerging PEVs loads into existing distribution networks especially in high penetration levels has challenged recently system planners and researchers as an attractive field of research. At the first glance, it seems that existing power cables and transformers in distribution networks should be upgraded to cope with new charging demands of PEVs. This solution will require huge amounts of investments as well as construction works in urban areas. However, using the emerging technology of smart grids, it might be fortunately possible to coordinate the PEV charging load without need to upgrading grids.

Coordination strategies for PEV charging are generally divided into two categories [3]. In the decentralized or distributed strategy, individual PEV owners have authority to make decision about the time and rate of charging of their car. All the network operator can do is to impose some price incentives in order to shift charging tasks to valleys of the load profile. Although this strategy offers more ownership authority to PEV owners, it may not ensure optimality in the charging of PEVs [3,4] as well as security concerns of power grids. In contrast, in central charging strategies, an aggregator centrally makes decisions about the time and rate of charging of PEVs to get the optimal solution [3,4]. Although a PEV can be plugged in by its owner at any time, the starting and finishing time of the charging task is remotely decided by the aggregator through smart outlets. The aggregator, acting as an interface between customers and the grid operator, provides charging services considering benefits of both sides of customers and the distribution company [5]. Employing smart grid facilities, the aggregator receives real-time status of loads and PEVs' battery state-of-charge (SOC) along with their arrival and desired departure times specified by PEV owners. Then, using this information,

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it tries to find an optimal charging schedule by minimizing the cost of purchased energy from wholesale market [6] in order to fulfill the owner-specified target SOC for each PEV if it is physically feasible and economically desirable. In the central charging strategy, PEV owner behavior can be static or dynamic. In dynamic behavior, PEV owners are entitled to plug-in and plug-out their PEV at any time and the aggregator has to update the load profile and obtain a new optimal schedule after coming or leaving a PEV. Compared with the static charging strategy where PEV owners should submit their schedule in advance, dynamic charging strategy offers more flexibility for PEV owners and of course it is more complicated and computationally demanding.

Valuable research is carried out in literature for coordinated charging of PEVs. Authors in [7] presented a methodology to minimize the cost PEV charging in order to balance the fluctuations of renewable energy sources. Electricity prices are used as incentives to consume electricity when the supply of renewable energy is high. In [8], the problem of PEV charging scheduling is studied from electricity market perspective with an emphasis on energy storage capability of PEVs to resolve uncertainty and inaccuracy of prediction. Authors in [9] proposed a charging coordination to minimize the cost of PEV charging using the game theory. The generation capacity and a multi-tariff electricity price are included in the method. In [10], the benefit and cost of PEV charging and discharging coordination strategy is assessed. The charging load of PEVs with their stochastic properties is considered using a two-stage optimization model with minimizing the peak load and load fluctuations. In [11], the impact of charging of PEVs with photovoltaic (PV) electricity on the performance of residential distribution systems is assessed. The intermittency of PV generation is modeled by Mont-Carlo analysis. Authors in [12] proposed an optimal scheduling for the PEV charging problem emphasizing on the number of charging and discharging cycles of PEV batteries to maximize the revenue of customers through returning stored energy of vehicles to the grid (V2G).

It is noted that voltage quality, as one of important features of power quality, is not considered in most PEV charging coordination works in literature such as ones reviewed above. It is evident that the network may experience poor voltages if only the rating of transformers and cables is considered in optimal PEV charging without paying attention to voltages. In fact, a limited number of papers considered voltage in PEV charging coordination. In [13,14], the optimal charging of PEVs is carried out in a multi-tariff environment so that the peak load does not increase and the load curve valley hours are used for charging with observing voltage limits. However, the problem is not presented in the standard form of an optimization programming problem (optimizing objective function subject to constraints); instead, the optimal solution is found through iterative series of power flows that can be time-consuming in real applications and may make the method inappropriate for online applications with dynamic behavior of PEVs, where the method should be run frequently with plugging in and out of PEVs. In [15], a quadratic programming is proposed for PEV charging with the objective function of minimizing power losses. In the mentioned papers, power losses are minimized in PEV optimal coordination. Although power losses are technically important, the aggregator may be more interested in a solution with the least cost, which can be obtained by minimizing cost of total energy purchased from the electricity market. The optimal solution with the least power losses does not necessarily results in a minimum cost; this will be numerically investigated in Section 'Case study and numerical results'.

On the other hand, it is worthwhile to note that the majority of papers, which have considered voltage limits in the optimal PEV charging problem, have assumed a balanced three-phase distribution system. However, most commercial PEVs in the real world are single-phase loads supposed to be charged from single-phase outlets at home or work. In addition, distribution systems are not necessarily operated in a balanced situation. Therefore, it is valuable to study the charging coordination of PEVs considering their real behavior as single-phase loads in unbalanced three-phase networks, which have special features compared with balanced systems and need more time-consuming models. Since PEV optimal charging methods have to be fast enough for online charging scheduling with dynamic behavior of PEVs, some innovative techniques should be employed to incorporate single-phase PEVs into the charging scheduling by not sacrificing the speed of the method. In literature, a very limited number of papers like [16] focused on single-phase PEVs in PEV optimal charging. Authors in [16] presented an optimal charging for single-phase PEVs in unbalanced distribution systems observing voltage limits and main transformer rated power. Voltages are calculated using a sensitivity-based method and a static scenario is considered in the algorithm with the objective function of maximizing the energy delivered to PEVs. Although this work bears some innovative concepts, its drawback is that neither the cost of purchased energy nor grid total energy losses is considered in the optimization problem. In fact, when the energy delivered to PEVs is maximized, not only the aggregator may encounter higher payments for purchased energy with on-peak tariffs, but also energy losses may be high and uneconomical. As a result, these two paramount features of distribution networks should be observed in PEV coordinated charging. It seems that to simultaneously optimize both objective functions of purchased energy cost and energy losses, multi-objective programming should be used. As another drawback of [16], its algorithm is run for each charging timeslot separately from others and consequently the interdependency of timeslots is not considered. In order to achieve a more optimal solution, it is necessary to solve the charging task as a multi-period optimization problem with interconnected timeslots.

Taking into account the above mentioned features and inspiring from [16], the main contribution of this paper is to present a multi-objective PEV charging scheduling in which PEVs are considered as single-phase loads supplied from an unbalanced three-phase network. It is formulated as a linear programming (LP) optimization problem able to get global optimal solution compared with Nonlinear programming (NLP) which can only get the local optimal solution [17]. The objective functions include minimization of energy cost purchased by the aggregator from the distribution company and the minimization of grid energy losses over the considered charging horizon. A multi-tariff scheme is assumed with different electricity prices to obtain payment of purchased energy. Also, fuzzy memberships are used to transform differently-scaled objective functions into the same scale of [0,1] to ensure the Pareto optimality of the multi-objective solution [18]. Phase voltages with respect to neutral are calculated using the sensitivity of individual phase voltage to PEV loads to observe voltage limits of single-phase customers. Because of its speed, the proposed method can be used in online charging schedules with dynamic behavior of PEVs where there is a need to constantly update the load profile and run the method after coming or leaving a new PEV.

The rest of this paper is organized as follows. In Section 'The proposed multi-objective optimal charging of single-phase PEVs', the formulation of the proposed multi-objective charging coordination of PEVs is presented with its objective functions and constraints. In Section 'Case study and numerical results', results of testing the proposed method on a residential distribution feeder are presented and discussed. The necessity for using multi-objective programming for PEV charging coordination is numerically shown in this section. Section 'Conclusions' concludes the paper.