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Decentralized electric vehicles charging coordination using only local voltage magnitude measurements

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ABSTRACT

A new decentralized approach for the electric vehicles (EVs) charging coordination in electrical distribution systems (EDS) is presented. The proposed EV charging method uses historical information of the voltage magnitudes at each node in which an EV is plugged in and ready to be charged, in order to coordinate the charging of the vehicles and avoid exceeding the operational limits of the EDS, as dictated by the moment of maximum consumption. Furthermore, information gathered via the Internet of Things (IoT), such as user preferences, the cost of energy and EVs' historical routes, can be used to deploy an economic EV charging method. The method was tested using an unbalanced three-phase EDS with 178 nodes, different EV penetration levels, and a fixed voltage regulator. Monte Carlo simulations have been implemented to analyze the performance of the proposed approach in different stochastic scenarios, with and without charging control, and with or without user priorities. Finally, the results are compared to the solution found by a centralized EV charging coordination method, based on a mixed-integer linear programming model.

1. Introduction

Climate change is causing severe impacts on society and natural resources worldwide. As a result, people are becoming more aware of the irreversible effects of greenhouse emissions and global warming. Thus, the utilization of environment-friendly technologies, such as electric vehicles (EVs) for urban transportation, is a prominent effort to reduce the consumption and dependency on fossil fuels [1]. In terms of efficiency, autonomy, comfort and cost/benefit, EVs are becoming more attractive than conventional internal combustion vehicles. Moreover, EV markets are expanding rapidly, especially in urban industrialized areas [2], and web-based technologies, integrated within the EVs, make it possible to interact with and supervise many features of the vehicles from a remote PC or from devices with Internet connection. This new paradigm is being coined as Internet of Things (IoT), in which a dynamic interaction between users, web-based applications, and EVs, is possible via IoT [3].

EVs, however, have a significant power consumption compared to conventional household appliances. Thus, the massive EV penetration into electrical distribution systems (EDS) represents a greater network usage of both, the primary and the secondary systems. The negative effects caused by high penetration of EVs are: elevation of peak load periods, low voltage profile, circuit overloads, increased power losses, and imbalance among phases [4,5]. These issues, though, can be reduced by using suitable charging coordination strategies. Since EVs are interruptible, and therefore controllable, electrical loads; the EV charging process can be rescheduled during low demand periods wherein the cost of energy is low, or in periods when the network has spare capacity to supply the EVs without overloading the EDS. Note that a proper EV charging coordination method should prevent distribution system operators (DSOs) from making expensive investments in the network to support the increasing EV penetration levels [5].

Typically, most EV charging coordination techniques use a control strategy that requires a centralized system that makes use of sophisticated measurement and communication infrastructures [4]. Centralized and distributed systems can be complex and inconvenient since they require intricate and expensive communication infrastructure and computational resources. Thus, there is a necessity for EV charging coordination solutions that are straightforward, adaptable, economic, easy to implement, maintain, and that efficiently coordinate the EV charging process; taking into account the EDS operational constraints. In this context, decentralized EV

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charging coordination is an interesting, cost-efficient approach that aims at scheduling the EVs to avoid voltage and capacity violations.

Relevant recent works on EV charging coordination are summarized in Table 1. The characteristics of each article are compared with the proposed approach in the last row of the table. Table 1 provides a bibliographic context and the key features of each method. As shown in Table 1, there are many works considering centralized EV charging coordination methods. More recently, distributed approaches have been proposed and intensively tested as well. Different from pure decentralized approaches, distributed methods use techniques that still require a certain degree of communication among devices to carry out the coordination process. Aggregator-based methods in MV/LV transformers or multi-agent systems (MAS) still require a communication infrastructure to transfer information among controllers. On the other hand, few studies analyze 100% EV penetration (i.e., one EV at each LV load node), which provides a more reliable assessment of the robustness of the method. Many proposals do not consider user priorities, which is a critical aspect, since users may have specific driving habits or require certain availability of their EVs, depending on their daily routines. Also, most simulations do not consider unbalanced three-phase distribution networks, which is important due to the unbalanced nature of LV grids. A more comprehensive survey of EV coordination methods before 2016, from the perspective of the proposed algorithms, can be consulted in Ref. [39]. To the best of our knowledge, a pure decentralized method, based on local voltage measurements and considering all of the highlighted features shown in Table 1, has yet to be proposed and tested.

In this work, a decentralized EV charging coordination method is proposed for coordinating EVs using only local measurements of voltage magnitudes at each charging point. The proposed approach does not require information about the network's topology, conventional demands, or the status among EVs. Instead, a stand-alone controller, installed in each EV charging point, executes a local charging algorithm, based on current and historical measurements of the three-phase voltage magnitudes at each node where a controllable charger is available. Assume that, in the absence of EVs, the distribution system has been properly planned to operate within constraints when the overall conventional demands reach their maximum levels. Then, based on the historical information of the voltage magnitudes at each charging point, the proposed controller locally dislocates the EV consumption to avoid violating the operational constraints of the system, i.e., transformer/line capacities and minimum voltage magnitudes. Thus, the proposed approach prevents DSOs from having to make further reinforcements to the system every time new EVs are required to be charged.

Furthermore, information obtained via IoT can be integrated into the proposed EV charging approach to incorporate user priorities that, based on the cost of energy at each period and the amount of energy required by each EV, minimizes the unsupplied demand at the lowest cost. Fig. 1 shows the information that can be gathered via IoT, such as charging preferences (which establishes the user priorities), cost of energy, historical routes and each EV charging controller information. It is worth noting that IoT is not a requirement for the proposed decentralized EV charging to work, but instead, it enhances the scope and practicality of the proposed method. Monte Carlo simulations are used to evaluate the performance of both methods, considering the stochastic nature of random variables, such as the time of arrivals and departures of the EVs, initial State of Charge (SoC), and conventional demands. Finally, the results of the proposed charging method are compared with a centralized three-phase EV charging coordination technique presented in Ref. [6], which is based on a convex mathematical optimization model, using a representative scenario.

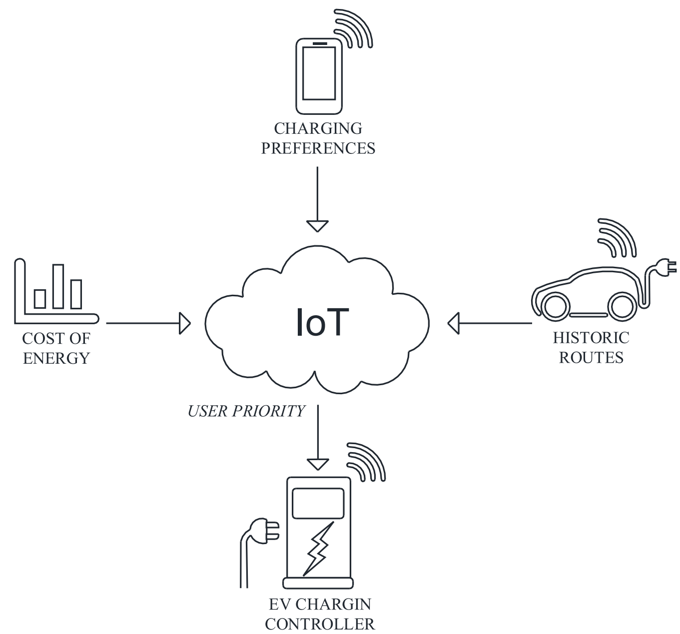

Fig. 1. The Internet of Things (IoT) and user priorities.

The main contributions of this work are as follows:

1. An innovative approach is presented for decentralized EV charging coordination, which aims at supporting the operational constraints of the EDS in realistic conditions and under stochasticity. The proposed approach uses only voltage magnitude measurements at the EV charging point and historical records of those measurements to deploy its control strategy, without any communication among controllers or with a central agent.
2. The proposed approach can be complemented via IoT, by considering user priorities, charging preferences, the cost of energy, and historical routes from the EVs.

2. Decentralized EV charging coordination

In this section, the proposed decentralized EV charging coordination approach is presented. The approach aims at satisfying the energy demanded by the EVs as quickly as possible, while avoiding exceeding the operational limits of the system, which are imposed by the steady-state operation of the network when controllable EVs are not being charged. The method only uses local voltage magnitude measurements at the EV connection point and does not require communication with a central server or among controllers. Also, it is intended for properly planned distributions systems, in which uncontrolled high penetration levels of EVs will certainly lead to operation limit violations. Thus, DSOs would need to either coordinate the charging process of the vehicles or invest in expensive reinforcements of the network to accommodate the new demand.

2.1. Assumptions

The following assumptions are adopted by the proposed decentralized EV charging coordination method:

1. Each user that owns an EV will have a charging controller installed at the charging point of their houses. The controller has voltage measurement capabilities and enough storage capacity to save the historical voltage magnitudes at the charging point.
2. The controller has an ON–OFF actuator that regulates the energy delivered to the EV when it is plugged. It also measures, processes