Engineering Applications of Artificial Intelligence 38 (2015) 45–58

Contents lists available at ScienceDirect

Engineering Applications of Artificial Intelligence

journal homepage: www.elsevier.com/locate/engappai

A multi-agent system for distribution grid congestion management with electric vehicles

Junjie Hu [a,*], Arshad Saleem [b], Shi You [a], Lars Nordström [b], Morten Lind [a], Jacob Østergaard [a]

[a] Center for Electric Power and Energy, Department of Electrical Engineering, Technical University of Denmark, Denmark
[b] Department of Electrical Engineering, Royal Institute of Technology, Stockholm, Sweden

ARTICLE INFO

Article history:
Received 11 December 2013
Received in revised form
6 October 2014
Accepted 22 October 2014
Available online 14 November 2014

Keywords:
Congestion management
Distribution grid
Electric vehicles
Multi-agent system
Resource allocation

ABSTRACT

Electric vehicles (EVs) are widely regarded as valuable assets in the smart grid as distributed energy resources in addition to their primary transportation function. However, connecting EVs to the distribution network and recharging the EV batteries without any control may overload the transformers and cables during peak hours when the penetration of EVs is relatively high. In this study, a two level hierarchical control method for integrating EVs into the distribution network is proposed to coordinate the self-interests and operational constraints of two actors, the EV owner and Distribution system operator (DSO), facilitated by the introduction of the fleet operator (FO) and the grid capacity market operator (CMO). Unlike the typical hierarchical control system where the upper level controller commands the low level unit to execute the actions, in this study, market based control are applied both in the upper and low level of the hierarchical system. Specifically, in the upper level of the hierarchy, distribution system operator uses market based control to coordinate the fleet operator's power schedule. In the low level of the hierarchy, the fleet operator use market based control to allocate the charging power to the individual EVs, by using market based control, the proposed method considers the flexibility of EVs through the presence of the response-weighting factor to the shadow price sent out by the FO. Furthermore, to fully demonstrate the coordination behavior of the proposed control strategy, we built a multi-agent system (MAS) that is based on the co-simulation environment of JACK, Matlab and Simulink. A use case of the MAS and the results of running the system are presented to intuitively illustrate the effectiveness of the proposed solutions.

1. Introduction

1.1. Impact of EVs on the distribution grids

EVs are widely advocated as a mean of personal transport and urban delivery because they can contribute to the reduction of CO_2 emission, especially when the recharging electricity is generated by renewable resources. However, the electric utilities must determine how to integrate the widely distributed EVs (especially when used by a large amount of the ordinary population) smoothly into the grid, i.e., manage the simultaneous charging of a large number of EVs without overloading the grid. Typically, a charging demand of 4 kW[1] represents twice the daily demand of a normal household. Several studies (Heydt, 1983; Lopes et al., 2011; Clement-Nyns et al., 2010; Green et al., 2011) have indicated that uncontrolled charging (also known as dumb charging) of EVs will challenge the capacity of the distribution grid. To address this challenge, the time-of-use tariffs or multiple tariffs charging scheme are used in the early stage to relieve the congestions in the peak hours (Shao et al., 2010). However, using tariffs solely is not adequate to eliminate the congestion because they merely shift the peak load to its neighboring period (Ma et al., 2013; Karfopoulos and Hatziargyriou, 2013). Fortunately, there is much flexibility in terms of EV charging that can be used to mitigate the overloading problems. An example to illustrate this point is an EV charging case in the Danish power systems. In (Wu et al., 2010), a Danish driving pattern analysis was presented, which stated that the average distance in Denmark is 42.7 km per day. With an

Abbreviations: DER, Distributed energy resource; EV, electric vehicles; FO, fleet operator; DSO, distribution system operator; SOC, State of charge of EV battery; MV/LV transformer, Medium voltage/low voltage transformer; MAS, Multi-agent system

* Corresponding author. Tel.: +45 93511212.
E-mail addresses: junhu@elektro.dtu.dk (J. Hu), Arshad.Saleem@ics.kth.se (A. Saleem), sy@elektro.dtu.dk (S. You), larsn@ics.kth.se (L. Nordström), mli@elektro.dtu.dk (M. Lind), joe@elektro.dtu.dk (J. Østergaard).

[1] Using Nissan Leaf as an example, the typical charger for the household is 4 kW.

http://dx.doi.org/10.1016/j.engappai.2014.10.017
0952-1976/

assumption of 0.15 kWh/km for the energy used per km of electric vehicles, one can deduce that the monthly energy requirement for an electric vehicle will be approximately 192 kWh. Using the Nissan Leaf (EV battery capacity of 24 kWh) as an example, this monthly energy requirement implied that the Leaf user must charge the EV approximately 8 times per month (192 kWh/ 24 kWh). However, owners will rarely fully discharge their EV before recharging it. Supposing the EV users charge the electric vehicles 20 times per month, this means 9.6 kWh of energy will be used each time. Considering the features of the charger[2], three hours are required for the charging. Normally, people leave home at approximately 7 AM in the morning and get home at approximately 5 PM in the evening, which means the EV can be charged at any three hours during the 14 h at home, in most cases.

1.2. Hierarchical control structures for EV integration management

Recently, much research has focused on the use of the EV charging flexibilities to coordinate the objectives and the constraints of the actors centrally as well as from market perspectives, e.g., to optimize the charging cost of EVs as well as to respect the hard constraints imposed by needs of the EV owner and the distribution grid operation. Regardless, in both types of coordination strategies, usually, the Fleet operator (FO) is proposed to manage the energy of EV charging as well as to provide ancillary services to the power system operator and these types of coordination forms a hierarchical control system. In addition to FO's role in this hierarchy, the role of the distribution system operator (DSO) is to operate, maintain and develop an efficient electricity distribution system. The objective of the EV owner is to minimize the charging cost given the condition that his/her driving requirements are fulfilled.

In Sundstrom and Binding (2012), a complex scheduling problem involving the EV owners, the FO and the DSO was analyzed centrally. The approach requires a complex interaction between the DSO and the FO in the upper level of the hierarchy. In each interaction, the FO will receive a specific grid constraint from the DSO and add it into the EV charging cost minimization problem in the lower level of the hierarchy. The results indicated that both the FO and the EV owners can achieve the objectives of minimizing charging costs and fulfilling driving requirements without violating the grid constraints. Lopes et al. (2009) proposed a conceptual framework consisting of both a technical grid operation strategy and a market environment to integrate EVs into the distribution systems. In that study, FOs manage the EVs, and the FOs prepare the buy/sell bids into the electricity market. Having this defined, a prior interaction with the DSO in the upper level of the hierarchical system must exist to prevent the occurrence of congestion and voltage problems in the distribution network. The smart charging algorithm was mainly designed for the operation of the DSO that can maximize the density of the EV deployment into the grid. It is also assumed that the grid has sufficient capacity to provide all of the power required by the EVs. With this assumption, the centrally smart charging approach was found to be effective. In Yao et al. (2013), the major objective of the upper-level of the hierarchy is to minimize the total cost of system operation by jointly dispatching generators and electric vehicle aggregators. The lower-level model aims at strictly following the dispatching instruction from the upper-level decision-maker by designing appropriate charging/discharging strategies for each individual EV in a specified dispatching period. In Wang et al. (2012), the proposed hierarchical large-scale EV charging management not only meets the requirement of system dispatching but also considers the customer satisfaction.

Although these proposed solutions are demonstrated to work efficiently for a limited number of EVs, totally centralized management in a hierarchical control system requires the acquisition and processing of an enormous amount of information in the case of a large penetration of EVs, such as (1) the battery model of each EV, along with the initial state of charge (SOC) and the desired SOC of each EV battery; (2) the driving pattern of each EV; (3) the grid constraint information from the DSO; and 4) electricity market information. This enormous amount of information would require significant computational resources, communication overhead and communication infrastructure cost. Research by Lyon et al. (2012) indicated that the benefits for the entirely centralized charging management might not justify the communication infrastructure cost. Alternatively, several means of solving the congestion problem in the distribution grid have been suggested from the market perspective. The paper by Andersen et al. (2012) conceptualizes several approaches, e.g., the distribution grid capacity market and the dynamic grid tariff (O'Connell et al., 2011), to address the distribution grid congestion. The conceptualized strategies for congestion management are evaluated in terms of their complexity of implementation, the value and benefits they can offer, as well as possible drawbacks and risks. Further on, the work by Hu et al. (2014) analyzed the shadow price-based grid capacity market scheme in which the FOs centrally schedule and control the charging of EVs in the low level of the hierarchy, and they negotiate with the market operator (distribution grid capacity market) in the upper level of the hierarchy on the limited capacity of the distribution grid if it is needed. The focus of the study by Hu et al. (2014) was the mathematical proof of the proposed market scheme. Some numerical case studies were presented to illustrate the effectiveness of the proposed solution. Besides, the authors in Qi et al. (2014) presented a hierarchical optimal control framework to coordinate the charging of plug-in electric vehicles in multi-family dwellings. The charging problems of a district, e.g., an area below one primary transformer, is decomposed into several subproblems that can be solved iteratively, locally, and in parallel, with updated information of Lagrangian multipliers broadcast by the centralized controller. In general, the concept of the market based control is applied in the upper level of the hierarchy in this study to solve the congestion problem of the primary transformer. The simulation result demonstrated that the proposed hierarchical charging strategy outperforms the centralized charging strategy from the perspective of computational requirements.

1.3. Multi-agent application for EV integration management in a hierarchical structure

To implement and assess both control strategies of the smart charging of EVs, especially the market-based coordination method in a hierarchical system, a multi-agent system (MAS)-based technology is very suitable (Jennings and Bussmann, 2003), the use of which can be justified by the following reasons:

- The increase in the complexity and size of the entire EV charging network raises the need for both distributed intelligence and local solutions, which fall into the scope of MAS-based technology.
- The information flow, optimizations and the negotiations that occur in the smart charging network of EVs can be well demonstrated and integrated into a MAS.

[2] Typically, in the European distribution network (residential area), three charging rate scenarios are considered: one-phase connections of 2.3 kW (AC 10 A × 230 V) and 3.7 kW (AC 16 A × 230 V) and three-phase connection of 6.4 kW (AC 16 A × 400 V). Using 3.7 kW as an example, this implies a charging time of approximately three hours (9.6 kWh/3.7 kW = 2.6 h). Note: the DC charging method is usually used for fast charging stations.