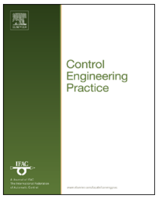
Control Engineering Practice 22 (2014) 147–162

Contents lists available at ScienceDirect

Control Engineering Practice

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



Electric vehicles charging control in a smart grid: A model predictive control approach[☆]

Alessandro Di Giorgio, Francesco Liberati[*], Silvia Canale

Department of Computer, Control, and Management Engineering "Antonio Ruberti," University of Rome "La Sapienza," Via Ariosto 25, 00185 Rome, Italy

ARTICLE INFO

Article history:
Received 7 March 2013
Accepted 12 October 2013
Available online 20 November 2013

Keywords:
Model predictive control
Electric vehicles
Demand side management

ABSTRACT

The paper presents an event driven model predictive control (MPC) framework for managing charging operations of electric vehicles (EV) in a smart grid. The objective is to minimize the cost of energy consumption, while respecting EV drivers' preferences, technical bounds on the control action (in compliance with the IEC 61851 standard) and both market and grid constraints (by seeking the tracking of a reference load profile defined by the grid operator). The proposed control approach allows "flexible" EV users to participate in demand side management (DSM) programs, which will play a crucial role in improving stability and efficiency of future smart grids. Further, the natural MPC formulation of the problem can be recast into a mixed integer linear programming problem, suitable for implementation on a calculator. Simulation results are provided and discussed in detail.

1. Introduction

The ongoing revolution introduced by the smart grid vision, prompted by the latest technological developments and a renewed attention to eco-sustainability, is quickly spreading also to the sector of mobility, traditionally dominated by fossil fuels. But still a number of issues have to be addressed in order to allow large-scale deployment of electric vehicle (EV) technology. Besides the very relevant challenges in terms of new business models and necessary infrastructure investments (Pieltain Fernandez, Gomez San Roman, Cossent, Domingo, & Frias, 2011), massive penetration of EV technology raises a series of technical problems: studies like (Clement-Nyns, Haesen, & Driesen, 2010; Putrus, Suwanapingkarl, Johnston, Bentley, & Narayana, 2009; Richardson, Flynn, & Keane, 2012) have clearly highlighted the impact that widespread diffusion of electromobility may have on distribution networks. A first consequence of the shift from fossil fuels to electricity in mobility will be a relevant change in load shape, with a significant increase of load on the distribution lines (according to Kempton & Tomic, 2005, the mechanical power of the US light vehicle fleet exceeds the electric power generation of the entire country by a factor of 24). Also, strengthening the couplings between the transportation and the electrical systems will have the effect of further increasing uncertainty and intermittency of profiles, which are typical "side effects" associated with distributed energy resources. As a result, grid management and network operation will become more complex, in terms of load balancing, survivability of network elements and overall power quality (Liu, Dow, & Liu, 2011).

Nevertheless, EV technology also represents a valuable opportunity. Since early works and seminal papers (Kempton & Tomic, 2005) it was recognized that a proper control of EVs at fleet level can contribute to stabilizing the network, integrating distributed energy resources and balancing intermittent renewable energy sources. Such results can be achieved by combining control of fleet charging process (Dallinger & Wietschel, 2011) with the control of reverse energy flows from the EVs to the grid. In particular, vehicle-to-grid power control (Kempton & Steven, 1997) appears as an effective way to exploiting the huge energy storage capabilities of EV fleets, and some works are beginning to appear (Dallinger & Wietschel, 2011; Kempton & Tomic, 2005) remarking the potentialities of vehicle-to-grid for demand side management (DSM) and provisioning of ancillary services.

This paper presents an event driven model predictive control (MPC) strategy aimed at providing cost-effective charging services to the EV users, in respect of drivers' preferences and seeking the tracking of a proper aggregated power profile, for providing ancillary services to the grid. Proper constraints are included in order to keep under control the cost for the single user and guarantee that technical limitations of devices involved are respected. The control action is limited in compliance with the

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Abbreviation: CS, charging station; CSCC, charging station control center; DSM, demand side management; DSO, distribution system operator; EV, electric vehicle; EVSP, electric vehicle service provider; MILP, mixed integer linear programming; MPC, model predictive control; UP, user preferences

[☆] This work is supported in part by the European Union FP7-2011-ICT-GC SMARTV2G project, under Grant agreement no. 284953.

[*] Corresponding author. Tel.: +39 0677274035.
E-mail addresses: digiorgio@dis.uniroma1.it (A. Di Giorgio), liberati@dis.uniroma1.it (F. Liberati), canale@dis.uniroma1.it (S. Canale).

0967-0661/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conengprac.2013.10.005

international standard IEC 61851 (ISO/TC/SC 69 Electric road vehicles & electric industrial trucks), which establishes that the charging power has to be semi-continuous, meaning that it is either zero or it ranges from a minimum positive value to a maximum positive value. The compliance with the standard is important because for technical reasons car manufacturers design the EVs so that they do not accept charging currents below a given threshold. Also vehicle-to-grid is included in the problem formulation and modeled in the same way. The proposed algorithm supports time varying prices and time varying power references and thresholds, thus enabling the controller, named charging station control center (CSCC), to react to price and volume signals, which are key tools at the base of innovative DSM schemes (Peeters et al., 2009). The CSCC is an aggregator (Bessa & Matos, 2012) which manages the EVs belonging to a specific load area. A load area is a proper portion of the low-voltage distribution grid defined by the distribution system operator (DSO) using proprietary information. The concept of load area has been consolidated within the ADDRESS project (ADDRESS Consortium, 2011), one of the most advanced initiatives in Europe on the topic of smart grids. Finally, the proposed solution is being investigated in the field of the European Union “SmartV2G” project, which aims at connecting the EV to the grid by enabling controlled flow of energy through safe, secure, energy efficient and convenient transfer of electricity and data (SmartV2G Consortium, 2013).

The remainder of the paper is organized as follows. Section 2 discusses the state of the art in load management and the proposed innovations. Section 3 details the reference scenario, the main actors involved, the equipment making part of the architecture and the use cases, from both drivers' and utilities' perspective. Section 4 presents the control system working logic, detailing the flow of operations and explaining the proposed MPC approach. Section 5 introduces the open-loop optimal control problem at the heart of the MPC approach. Section 6 shows how the open-loop optimal control problem can be handled by achieving an equivalent semi-continuous linear programming problem. Finally, simulation results are discussed in Section 7, while conclusions and future works are presented in Section 8.

2. State of the art and proposed innovation

The emerging concept of smart grid is based on the deployment of a multilevel control architecture, with the aim of reaching a deeper integration between generation and demand. Demand response, DSM and active demand are terms which all refer to new central paradigms evoked for referring to a direct influence of demand on the technical and economical balance of the grid (Rahimi & Ipakchi, 2010). Load management problems have received an increasing attention from academics and industry during the last decade. Industry has been the driving sector for many years and it is also the first one for which pioneer DSM programs have been proposed (Ashok, 2006; Ashok & Banerjee, 2000; Middelberg, Zhang, & Xia, 2009). Load shifting concept is being deeply investigated also in the residential sector, with the purpose of optimally controlling smart household appliances, storage devices and local renewable energy sources (Di Giorgio & Pimpinella, 2012; Matallanas et al., 2012; Newsham & Bowker, 2010). The concepts established in the aforementioned works in the field of load management find a natural application also to electromobility. An interesting approach for coordinating charging operation of multiple EVs in a smart grid system is presented in Deilami, Masoum, Moses, and Masoum (2011). An MSS (maximum sensitivities selection) optimization problem is established, with the aim of minimizing cost of energy consumption and network losses. EVs are divided into priority groups, depending on user preferences (UP) and sensitivity of system losses due to each EV. Moreover, voltage constraints at each charging station (CS) of the network and congestion constraints are considered. Grid variables are computed through simulation, via a standard Newton-based load flow routine. The main drawbacks of this work are: (1) charging control signals are continuous in nature but not IEC 61851 compliant; (2) there is not a strict control over the time needed to provide the charging service and on the desired final state of charge of the batteries; (3) backfeeding is not considered. These are rather common drawbacks in the relevant literature.

A similar approach is presented in Richardson, Flynn, and Keane (2010), where the authors set up an optimization problem seeking to maximize the amount of energy available for charging operations, while considering constraints on voltage levels, charging rate changes, network congestion and thermal loading of network components. Voltage levels and thermal loadings are calculated based on load flow analysis. Interestingly, a weighted objective function is proposed, in order not to penalize charging points characterized by a high sensitivity (in radial networks, voltage level is generally more sensitive to addition of load far from the transformers). Among the drawbacks of the work there is the fact that charging control signals are continuous in nature but not IEC 61851 compliant; moreover, UP are poorly modeled (the overall energy available for charging operations is maximized, not taking into account the precise amount of energy demanded by each EV, or the time preferences for charging operations set by the users). Also in this work the authors do not take into account the possibility of delivering *active demand* services to the grid.

An original control approach is presented in Studli, Crisostomi, Middleton, and Shorten (2012). The charging process is controlled by using a distributed AIMD (additive increase–multiplicative decrease) feedback control algorithm, known for its use in telecommunication resource management problems. The main advantage of the approach is related to its distributed nature, which keeps low the number of communications needed to achieve the objectives. The main drawbacks are also related to the AIMD concept. It requires that the EVs have the ability to vary their charge rate in a continuous manner from zero to a maximum value, a very common assumption which, again, is not compliant with the standard IEC 61851. Moreover, the vehicle-to-grid concept is not considered in that work.

Another interesting contribution from the control methodology point of view is given in Bashash and Fathy (2011), where the authors apply sliding mode control principles to achieve stability and robustness with respect to system uncertainties. The authors derive a simple centralized control strategy in which a unique charging rate signal for all the EVs is adjusted in order for the aggregated charging power profile to track the available power trajectory resulting from both renewable and traditional generation. The interesting achievements of this work are the stability and robustness to the collective effects of system uncertainties (in particular, drivers arrival at the CSs and power generation from renewable energy sources). However, only the high level behavior of the system is investigated; driver preferences are not considered in the problem formalization and the applied control is the same for all the EVs. So doing the benefits for drivers are not differentiated in relation to their level of flexibility.

Another work taking inspiration from communication engineering is Fan (2012), in which the author proposes a distributed framework for EVs charging, based on the concept of congestion pricing in Internet traffic control. The work is based on concepts already well known and studied also in smart grid research: each EV is modeled as an agent with an associated utility function. The objective of the agent is to maximize its individual surplus (the utility minus costs). The cost of energy is calculated by the agent based on the unit price of energy, which is centrally updated