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Energy management of an experimental microgrid coupled to a V2G system

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HIGHLIGHTS

- Energy hubs are used to model a microgrid and an electric vehicle charging station.
- A hierarchical control structure is applied to the system.
- A charging station management algorithm is proposed.
- The controller handles the switching between the electrolyzer and fuel cell.

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ABSTRACT

This paper presents an algorithm for economic optimization of a laboratory microgrid. The microgrid incorporates a hybrid storage system composed of a battery bank and a hydrogen storage and it has a connection with the external electrical network and a charging station for electric vehicles. To study the impact of use of renewable energy power systems, the microgrid has a programmable power supply that can emulate the dynamic behavior of a wind turbine and/or a photovoltaic field. The system modeling was carried out using the Energy Hubs methodology. A hierarchical control structure is proposed based on Model Predictive Control and acting in different time scales, where the first level is responsible for maintaining the microgrid stability and the second level has the task of performing the management of electricity purchase and sale to the power grid, maximize the use of renewable energy sources, manage the use of energy storages and perform the charge of the parked vehicles. Practical experiments were performed with different weather conditions of solar irradiation and wind. The results show a reliable operation of the proposed control system.

1. Introduction

Efficient energy generation and consumption is a key factor to achieve ambitious goals for sustainable development and activities related to air pollution and climate change. Energy generation fundamentals of today are about to undergo a profound change: affordable fossil fuel reserves are being reduced every year while, at the same time, energy demand increases in every country. Moreover, the aim to reduce greenhouse gas emissions is moving its attention to more environmentally-friendly and sustainable energy sources. With an increased utilization of small distributed energy resources for generation of electricity and heat [1], renewable energy generation will constitute an important part of the overall energy scenario in the coming years.

One of the main problems associated with these kind of systems is the reliability and quality of the power supply. As a matter of fact, since the renewable source is intermittent, unpredictable fluctuations may appear in power output [2]. One way to overcome this problem is by including intermediate storage, such as batteries, water pumping, super-capacitors, compressed air, fly wheels, superconducting magnetic energy storages, etc. [3].

The use of storage systems enables the opportunity to decide the microgrid optimal operating point both in islanded mode and connected to the grid, being possible to manage the appropriate time to exchange energy with the external network. There are several energy storage technologies and the possibility of hybridization among them results of great interest [4],[5]. Specifically, the combination of hydrogen storage together with electric batteries

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and supercapacitors seems to be a suitable solution for renewable generation [6]. The use of hydrogen for storing electrical energy from renewable sources is based on the possibility of producing hydrogen by electrolysis, store it and subsequently use it again to generate electricity through fuel cells.

A structural solution that has been studied in recent years is the splitting of the electrical network into smaller self-generation units based on renewable energy where the use of energy storages compensate the fluctuations in renewable generation and the randomness of consumer behavior. Thus the concept of microgrid, introduced by Refs. [7], becomes a powerful tool to improve the electrical system quality and reliability. According to [8] a microgrid can be seen as a set of loads, generators and storages whose management can be done independently or connected to the external network in a coordinated way to contribute to the whole system stability.

With an increasing demand on improving productivity and efficiency, the operation requirements of energy systems are getting tighter. It is known that an optimal operation of each subsystem composing the energy plant does not ensure the optimal operation of the whole system leading to an even not admissible behavior. This makes necessary coordination between the elements of the whole plant. This is typically carried out by a supervised automatic system which relies in an upper level in the control hierarchy of the plant. From the efficiency point of view, the best control technique should take into account simultaneously the efficient operation of each subsystem while quality requirements are fulfilled.

Model Predictive Control (MPC) is the most natural approach to the optimal control of processes subject to constraints. This explains why MPC is the advanced control strategy that has the greatest acceptation in process industry. However, there are still many open issues related to MPC techniques to be applied to energy systems, such as cooperation, robustness, real-time optimization, etc. that must be deeply explored.

In general, microgrids management is carried out by heuristic algorithms [9], although there are applications that use MPC strategies, such as those presented in Refs. [4] and [10]. Optimal control of distributed energy resources using model predictive control with battery storage system is developed in Ref. [11]. In the case of hybrid storage systems the MPC appears to be a good solution as shown in Refs. [12,13,5].

On the other hand, V2G systems (Vehicle-to-grid) consist of the use of electric car's batteries, during periods when they are not being used, as energy storages for an electrical network. It is estimated that a vehicle is in motion only 4% of time, so the rest of the time it could be available as an electrical energy storage unit [14]. Furthermore, in normal use, the car's batteries are recharged overnight (which is the period of low electricity demand) and are parked in the workplace during periods of high electrical demand, so this power could be used to meet peak demand. This storage capacity is especially useful with renewable energy sources, because its fluctuating nature makes it harder to adjust production and demand.

In addition, V2G systems enable to set new business models with new actors, such as Load Managers, that would be responsible for recharging infrastructure, providing service to vehicles, buying or selling electrical energy and building relationships with the network managers. In the last years control algorithms for charging electric vehicles in intelligent networks have appeared in literature, on one hand, to offer better charging service to attend drivers demand preferences and secondly to ensure a given power profile on the network, also considering various restrictions both, in vehicle, the station charging and network. In Refs. [15] and [16] this problem is solved by real-time optimization algorithms, whereas in Ref. [17] an MPC based algorithm is presented. Also, solutions based on hierarchical distributed algorithms were presented in ([18–20]).

Several works ([21–23]) use the hysteresis band (HB) method for energy management of microgrids with hybrid storage. Regarding the performance advantages of MPC over optimized hysteresis band, there are already several papers comparing these approaches and others ([24–26]). The main difference between MPC and HB is that MPC guarantees optimality while HB does not. MPC solves an optimization problem each sampling time to determine minimal running cost while meeting the demand and considering technical and physical limits. A dramatic reduction in operation cost can be observed when comparing both techniques [27].

Most of the algorithms presented in literature use very simplified models of power systems, vehicle motion and load characteristics. One of the approaches, namely the modeling framework called Energy hubs [28], allows the integration of different forms of production and storage of a microgrid, V2G system [29] and the interconnection of different microgrids or a microgrid connected to a electric network.

The control of hybrid energy systems including renewable and no-renewable generation is an important problem to be studied in the following years to allow the optimal operation of these new generation units. The integration of V2G systems can be a key factor in network stability guarantee against load fluctuations. In this context the objective of this paper is to present an MPC algorithm for optimizing a microgrid coupled to a V2G system consisting of four charge stations of electric vehicles. The proposed algorithm performs the management of the use of renewable energy sources, energy storage units, vehicles charge and the purchase and sale of electric power to the external network.

The rest of the paper is organized as follows. Section II describes the system under study, while section III presents the energy hub modeling framework. Section VI presents the microgrid modeling and section V proposes a hierarchical MPC. Finally, section VI illustrates the potential of the proposed algorithm in a experimental study. The paper ends with some conclusions.

2. V2G experimental microgrid

In this paper the experiments were carried out at HyLab microgrid connected to an electric vehicle charging system. This microgrid was designed to study control strategies applied to energy management of a network based on renewable energy sources and hydrogen storage ([10,24,30]). The facility has special features that allow the implementation and study of different operating modes and control strategies. Fig. 1 shows the outline of the studied system.

To replicate renewable energy systems, the microgrid has a programmable power supply that can emulate the dynamic behavior of a wind turbine and/or a photovoltaic field. It also includes a battery bank, an electronic load to emulate different consumption systems and, finally, includes a hydrogen storage system comprising a PEM (Proton Exchange Membrane) electrolyzer to produce hydrogen, a metal hydride tank to store hydrogen and PEM fuel cell to produce energy. The electric car charging station has the capacity to charge four cars simultaneously. The charging station was emulated by a hardware-in-the-loop methodology. The dynamics of the electric vehicle batteries were simulated by a Simulink model and interfaced with the microgrid through the programmable power supply and the electronic load. The technical characteristics of the equipments are summarized in Table 1.

From the microgrid operation point of view, usually the energy produced does not match the demand. Then, the excess of energy from renewable sources can be stored in batteries or used to