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Fuel cell cars in a microgrid for synergies between hydrogen and electricity networks

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HIGHLIGHTS

- A novel concept of a flexible energy system that uses fuel cell cars as dispatchable power plants.
- Synergies between hydrogen and electricity networks by operating of fuel cell cars in a microgrid.
- A robust min-max model predictive control scheme for optimal dispatch of the fuel cell cars.
- A novel model predictive control scheme to govern the system operation.

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ABSTRACT

Fuel cell electric vehicles convert chemical energy of hydrogen into electricity to power their motor. Since cars are used for transport only during a small part of the time, energy stored in the on-board hydrogen tanks of fuel cell vehicles can be used to provide power when cars are parked. In this paper, we present a community microgrid with photovoltaic systems, wind turbines, and fuel cell electric vehicles that are used to provide vehicle-to-grid power when renewable power generation is scarce. Excess renewable power generation is used to produce hydrogen, which is stored in a refilling station. A central control system is designed to operate the system in such a way that the operational costs are minimized. To this end, a hybrid model for the system is derived, in which both the characteristics of the fuel cell vehicles and their traveling schedules are considered. The operational costs of the system are formulated considering the presence of uncertainty in the prediction of the load and renewable energy generation. A robust min-max model predictive control scheme is developed and finally, a case study illustrates the performance of the designed system.

1. Introduction

Power systems are accommodating an increasing amount of renewable generation. However, Renewable Energy Sources (RES) such as the sun or the wind are variable, uncertain and not dispatchable, and therefore electricity is not always produced when it is needed by the users. Flexibility sources like dispatchable generation, storage, demand side response, and increased interconnection are needed to integrate more renewable power generation to power systems [1,2].

Electric Vehicles (EVs) can provide the flexibility needed in future electric power systems. Although plug-in EVs represent a new source of variability due to their charging needs, this variability can be managed via smart charging strategies [3], and the vehicles' batteries can also be used to store surplus renewable generation. Moreover, plug-in EVs can become dispatchable power plants by providing power or balancing services via vehicle-to-grid (V2G) technology [4]. Fuel Cell Electric Vehicles (FCEVs), with hydrogen as fuel, can be used to support the operation of power systems with a large participation of RES. They are particularly suited to provide peak power or spinning reserves to the grid [5,6]. Because they use hydrogen as a fuel, they do not draw power from the grid, and if aggregated, they can provide large amounts of power. In contrast to plug-in EVs, if FCEVs have a connection to a hydrogen source, they can be operated continuously regardless of the level of fuel stored in their tank [5]. Through the use of FCEVs for both transportation and power generation, we can explore the

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synergies that can be created between hydrogen and electricity networks.

In this paper, we present the Car as Power Plant (CaPP). This concept, originating from van Wijk, is extensively described in [7]. CaPP introduces a flexible multi-modal energy system that uses FCEVs as dispatchable power plants [8]. It is based on the fact that FCEVs, when parked, can produce electricity from hydrogen in a cleaner and more efficient way than the current power system, thereby producing waste products (water and heat) that can be re-used [7,9]. Since cars are used for driving only around 5% of the time, there is a big potential to replace peak power plants with a large fleet of FCEVs or to reduce the need to build new plants in the future. Additionally, heat generated in the fuel cells can be used locally if the FCEVs are connected directly to a building's heat network [6].

The CaPP concept can be implemented in different settings and for different types of applications. When applied in a parking lot, a large fleet of parked cars can be used to provide power to the grid through an aggregator that sells power on behalf of the drivers. In residential microgrid settings, residents of the neighborhood can use their FCEVs to provide power to the local grid at times of low renewable power generation. In buildings with high electricity and heat demand, such as hospitals, the CaPP system can be implemented not only to use the electricity and heat from vehicles, but also to provide a large back-up capacity to the building.

In the current paper, we explore the possible synergies between hydrogen and electricity networks using the residential microgrid CaPP case. We consider a residential microgrid with distributed generators that are used to serve local loads and to produce hydrogen, which acts as energy storage medium. This gaseous fuel is used by cars to drive, and additionally, it can be used to generate power when renewable power sources are scarce. This system is studied from the operational control perspective, as operational control is one of the main challenges in the implementation of microgrids [10].

The operational control aspects to take into account in the CaPP microgrid are the scheduling of the FCEVs and the electrolyzer. In the literature, the scheduling problem of grid-integrated vehicles in microgrids is usually addressed with centralized optimization approaches, where the resources from plug-in EVs are managed by minimizing power losses in the system [11] or by minimizing the operating costs [12]. In a microgrid with renewable resources, an electrolyzer and vehicle-to-grid (V2G) power from FCEVs, the V2G scheduling problem is addressed by minimizing the power imported from the grid [13]. The operation of electrolyzers is also addressed with optimization approaches in the literature [14–16]. Similar control objectives are used, for example, maximizing the profits from wind power export to the grid while taking into account the hydrogen demand [14]. In [17] the sizing and techno-economic aspects of a PV-to-hydrogen system with fuel cell buses are studied using a simple control algorithm.

Model predictive control is used in the operation of microgrids in [18]. The optimization problem in [18] is formulated as a mixed integer linear programming problem. Herein, it is assumed that the prediction of the electrical load of the microgrid is accurate and there is no uncertainty in the system. To deal with the uncertainty in the prediction of the load and generation of renewable energy sources, robust control techniques are developed in [19,20]. A stochastic optimization approach is used in [19] where a set of scenarios are selected for the uncertainty in the system. However, the selection of a reliable set is not always possible. In [20], the authors develop a min-max optimization method to operate a microgrid. However, the use of the fuel cells and electrolyzer, in addition to the connection of the microgrid to the power grid and exchange of electricity is not considered in [20].

In this paper, a model is developed that describes the power generation of the fuel cell cars while the transportation aspect of the cars is taken into account. Further, a unified model is derived that describes the economic dispatch problem of a microgrid including a fleet of fuel cell cars, a water electrolysis system, and RES in the form of wind turbines and PV systems. A model predictive control scheme is developed to govern the system operation while the uncertainty in the prediction of the electrical load and power generation of RES is taken into account. The min-max optimization problem that arises in model predictive control is converted into a mixed integer linear programming problem. Realistic data for the behavior of drivers based on the survey of the Dutch Ministry of Infrastructure and renewable energy generation based on the Dutch weather data are used to illustrate the behavior of the system.

The rest of the paper is organized as follows: In Section 2 we describe the CaPP microgrid system. In Section 3 the system model is developed. Section 4 develops an optimization problem to be used in the control system. In Section 5, a case study is simulated and, finally, Section 6 concludes the paper.

2. The CaPP microgrid system

2.1. Description of the system

The CaPP microgrid consists of a group of residential loads, a PV system, a wind turbine, an electrolyzer, and a hydrogen storage system, as depicted in Fig. 1. A centralized PV system and also a wind turbine are used to provide electricity to the households. When there is a surplus of renewable power generation, it is used to produce hydrogen via electrolysis of water. The hydrogen produced is compressed and stored in a central storage tank, which is used as a refilling station for FCEVs. The FCEVs are used both for the transportation of residents of the neighborhood and also the generation of electricity inside the neighborhood. The energy management system controls the flows of electricity and the scheduling of FCEVs as power plants.

A side product of generating electricity in each fuel cell stack is heat. In order to keep the temperature of the fuel cell stack inside the desired range, FCEVs are equipped with a relatively big radiator and cooling fans. We assume that in the stationary mode, when the FCEVs are used to generate electricity for the microgrid, the fuel cells are only operated at partial load. In other words, the maximum power generation of a fuel cell in the stationary mode would be a small fraction of its nominal power. As a result, the on-board utilities of an FCEV would be still able to regulate the fuel cell's temperature, even at standstill. It is worth mentioning that the use of waste heat from the vehicles can be accommodated by heat exchange equipment suggested by [6]. Others like [5] reject the idea given the additional equipment needed and complexity involved, but this could be solved by centralizing the heat exchange system. However, in this paper, we focus on the electrical power generated by the fuel cells. The use of the fuel cell's heat and their corresponding models is considered as a topic for future research.

A common feature in most of the RES, such as wind and solar energy, is the variation in power generation due to fluctuations in the weather conditions. The CaPP concept brings the opportunity to create a microgrid system with RES and without wind and solar energy curtailment. We assume that the microgrid is connected to the power grid and that exchange of electrical power may happen in both directions. It is assumed that the cost of power exchange between the microgrid and the power grid is determined by the power grid operator. Based on the load and the generation profile of the other generation units in the power network, the