Energy 115 (2016) 38–48

Contents lists available at ScienceDirect

Energy

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

Control and operation of power sources in a medium-voltage direct-current microgrid for an electric vehicle fast charging station with a photovoltaic and a battery energy storage system

Pablo García-Triviño [a], Juan P. Torreglosa [b, c], Luis M. Fernández-Ramírez [a, *], Francisco Jurado [c]

[a] Research Group in Electrical Technologies for Sustainable and Renewable Energy (PAIDI-TEP-023), Department of Electrical Engineering, EPS Algeciras, University of Cádiz, Avda. Ramón Puyol, s/n, 11202, Algeciras, Cádiz, Spain
[b] Electrical Engineering Department, University of Huelva, Carretera Palos-Huelva, s/n, 21071, Palos de la Frontera, Huelva, Spain
[c] Research Group in Research and Electrical Technology (PAIDI-TEP-152), Department of Electrical Engineering, EPS Linares, University of Jaén, C/Alfonso X, nº 28, 23700, Linares, Jaén, Spain

ARTICLE INFO

Article history:
Received 25 April 2016
Received in revised form
8 August 2016
Accepted 29 August 2016
Available online 10 September 2016

Keywords:
Battery energy storage system
Charging station
Control
Electric vehicles
Medium voltage direct current

ABSTRACT

Although electric vehicles (EVs) are experiencing a considerable upsurge, the technology associated with them is still under development. This study focused on the control and operation of a medium-voltage direct-current (MVDC) microgrid with an innovative decentralized control system, which was used as a fast charging station (FCS) for EVs. The FCS was composed of a photovoltaic (PV) system, a Li-ion battery energy storage system (BESS), two 48 kW fast charging units for EVs, and a connection to the local grid. With this configuration and thanks to its decentralized control, the FCS was able to work as a stand-alone system most of the time though with occasional grid support. This paper presents a new decentralized energy management system (EMS) with two options to control the power sources of the FCS. The choice of the power source depends on the MVDC bus voltage, the state-of-charge (SOC) of the BESS, and the control option of the EMS. This control was tested by simulating the FCS, when connected to several EVs and under different sun irradiance conditions. Simulation results showed that the FCS operated smoothly and effectively, which confirms the feasibility of using this technology in EVs.

1. Introduction

Climate change and dependence on fossil fuels in the transportation sector have generated serious environmental problems [1]. The situation has worsened because of stricter regulations on CO_2 and NO_x emissions in passenger cars and light commercial vehicles. The search for possible solutions has brought plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs) into the spotlight, and has made the technology associated with them a research priority [2].

Nevertheless, there are still many obstacles to the widespread use of PHEVs and EVs. Although the operation costs of EVs are lower than those of Internal Combustion Engine vehicles, EVs are very expensive to purchase until now [3], and fast charging stations (FCSs) are not generally available. Another problem is the negative impact of the FCS on the electrical grid (harmonics, voltage outages, and fluctuations) [4–6]. Since the increased use of EVs also affects electricity market operations [7], careful planning is also required [8–11]. Moreover, in both cases, another factor to consider is whether the FCS has a battery energy storage system (BESS) which, in case of renewable supplied systems, is essential (together with a suitable smart charging strategy) to cope with the renewables uncertainty [9,12].

To be comparable with internal combustion engine vehicles, the charge time of EVs should be as short as possible. Thus, it is clear that EV penetration is linked to the development of commercial FCS composed by several high power points of charge equivalent to petrol stations.

These FCS present two topologies: (i) the first one based on a common AC bus which feds each one of the AC-DC EV chargers, and (ii) the second one based on a common DC bus feeding the different

---

* Corresponding author.
E-mail addresses: pablo.garcia@uca.es (P. García-Triviño), juan.perez@die.uhu.es (J.P. Torreglosa), luis.fernandez@uca.es (L.M. Fernández-Ramírez), fjurado@ujaen.es (F. Jurado).

http://dx.doi.org/10.1016/j.energy.2016.08.099

DC-DC chargers. Both topologies are regulated by various norms [13,14]. Specifically, the IEC 61851-1 establishes four modes of charging, depending on the following: (i) the quantity of power received by the EV; (ii) the type and level of voltage; (iii) the communication mode between the charging station and the EV; and (iv) the location of the protections. Experimental results presented in Refs. [15–17] demonstrated that the latter option is the most viable solution due to the nature of loads, fewer conversion stages and easy integration of distributed generation or energy storage systems.

The technical literature associated with DC-based FCS provides support to this topology from different approaches.

To start with, there are works focused on studying the FCS system by itself independently of its interaction with the grid: specifically the topologies of the converters that compose them (i.e. an AC/DC converter for the grid interface and multiple DC/DC converters for charge or discharge of EVs) and their coordinated operation as a system. In 2013, Dubey et al. [18] presented an average-value modelling of a FCS composed by a full-bridge rectifier to convert AC power to DC power, a boost converter to step-up the input voltage to a level compatible to the EV battery voltage and a full-bridge forward DC-DC converter with a low-pass filter that isolated the battery from the supply power system. This average value model was built in Simulink and validated against a switching model developed using PSCAD/EMTDC and against actual measurements taken at an EV charging facility. The analysis suggested that the proposed model was sufficiently accurate in approximating the EV charger during steady-state operation. More recently, a new type of converter that allowed the connection of multiple DC/DC fast chargers to the grid was proposed in Ref. [19]. This converter extended the power range of charging stations to megawatt level. A neutral point clamped converter was used to increase the power capacity of the system since the DC-link bus was doubled. However, because of the random nature of the loads, the proposed converter required its DC voltages to be balanced for correct operation. Thus, its focus was the design of a control system based on achieving balance so as to reduce the DC current flow. It was demonstrated by studying the system performance under balanced and unbalanced scenarios during steady-state operation.

Other approach taken by several works is to study the impact of the FCS in the utility grid in terms of grid voltage support, voltage drop and reactive power control [13,20]. The common approach followed by these works is to focus their studies on the converter that connects the FCS with the grid and its control. It was presented in Ref. [20] an energy management and control study of an EV charging station that was modelled and simulated in SimPowerSystems of MATLAB along with the toolbox Opal-RT real-time simulation technology. The control of the grid side converter and the EV chargers was decoupled: the first one was in charge of controlling reactive power, AC system bus voltage and DC-link voltage control, and the others were based on constant current and constant voltage control. The charge and discharge of EV were subject to dynamic price framework. It led to different charge/discharge modes that were simulated independently but it was not specified how the transitions among the modes were done. Ying et al. [13] modelled an FCS in PSCAD/EMTDC to study the impact of EV fast charging on the distribution network where the FCS was connected. The control of the grid-interface power converter (AC/DC) and each EV charger (DC/DC) were decoupled. The AC/DC converter was controlled so that it injected reactive power into the grid for voltage regulation and power factor correction. A constant DC-link voltage was also maintained at the common DC bus. At the same time, DC/DC converters were able to charge or discharge the EVs. This paper focused solely on the charging process based on a constant current/reduced constant current approach under different scenarios (grid to vehicle, vehicle to grid and vehicle to vehicle) and the transition among operating conditions was not considered.

Other works, instead of focusing only in the effect of the FCS in the node where it was connected to the grid, studied its impact when connected to different nodes by using simulations. In these works, the systems were modelled by means of simply approaches in which power converters were regarded as negligible. Dealing with a large number of EV chargers at different points requires a study on suitable scheduling strategies and two approaches have been proposed: centralized or decentralized. On the one hand, Richardson et al. [21] proposed a strategy for optimizing the charging rates of EVs based on a local control charging method while maintaining the network within acceptable operating limits. The results obtained were compared to those of a charging method with centralized control whereby a single controller managed the charging rates of all the EVs on the network, simultaneously. It was concluded that the use of local controllers was viable and had the advantage of not requiring communication structure. Nevertheless, precisely for this reason, a larger safety margin (energy storage system capacity) was required to maintain operating limits. However, the advantages of distributed storage systems to maintain the grid control was also supported by centralized approaches as showed in Ref. [22], that proposed a centralized control of the charging/discharging of EVs distributed in a grid whose stability was maintained by peak shaving and valley filling. In summary, EV batteries were used as distributed energy storage systems to stabilize grid performance.

The advantage of adding energy storage systems to FCS is supported by different works by experimental essays. In Ref. [16], it was carried out experimental tests of a FCS with two power DC/DC converters of similar rated power: one to charge the EV and another to charge/discharge the energy storage system acting as a buffer to support the grid during fast charging or even under islanding operation. It was demonstrated the advantages of this DC architecture in terms of performance and showed the real performance of different kinds of battery pack integrated in a smart grid. New experimental test of battery-assisted FCS based on a DC architecture were shown in Ref. [17] and supported this topology. Specifically, the impact of different seasons on the charging rate was evaluated concluding that battery temperature strongly influenced its charging behaviour, ambient temperature influenced battery temperature and charging rate during summer was higher than that during winter. Besides, it was drawn that the use of batteries improved the performance of EV chargers minimizing grid stress and maintaining the quality of grid electricity.

These last experimental studies highlighted the suitability of architectures including batteries as energy storage for the integration of renewable energy sources as a replacement for the utility grid connection. However, in the literature, there are very few papers considering charging stations supplied by renewable energies replacing the grid or working together. These works could have been classified in some of the groups presented in this introduction but they have been put apart to highlight their scarcity. In 2012, the first studies on these systems were published in the form of conference papers [23,24]. Reed et al. [23] described the modelling approach and simulation results performed in PSCAD of the components of a medium-voltage direct-current (MVDC) microgrid-based FCS. Their study presented models of renewable energy generation (including wind and solar energy), energy storage (in battery form), and loads (EVs) at a direct medium-voltage connection. The FCS model consisted of three photovoltaic (PV) arrays, three EV level 3 DC fast chargers, and bidirectional power flow capability to and from the DC grid. Simulations showed the isolated operation of each of these models including their power