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Energy Procedia 105 (2017) 2317 – 2322

Energy Procedia

The 8th International Conference on Applied Energy – ICAE2016

Charging architectures integrated with distributed energy resources for sustainable mobility

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Abstract

This paper introduces a study on the charging infrastructures, integrated with distributed energy sources, showing their ability to support the electric and hybrid mobility in a smart grid scenario. This analysis starts from a description of the main AC and DC architecture and then goes through the advantages derived by the integration of renewable energy sources within the existing electric power network. A section of this paper is then dedicated to the main technologies of energy storage systems, which allow and support the integration of unpredictable energy sources into the grid. Finally, the power on-board and off-board vehicle charging devices are analyzed with specific focus on PWM control schemes, for the regulation of AC/DC and DC/DC power converters, and on grid operations (V2G) related to different aggregation schemes.

Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.

Keywords: Electric Vehicles, EV Charging, electromobility, grid integration

1. Introduction

Electric vehicles (EV) and renewable energy sources play a fundamental role in reducing huge amount of carbon emissions caused by both the transportation and power generation sectors. In fact, road vehicles powered by full electric or hybrid power drives represent a very interesting chance to solve the well known issues concerning liquid fossil fuel dependence. For this reason. a new transition towards sustainable transport systems is becoming an urgent necessity to be faced by the different players involved in these sectors. This paper gives an overview on electric vehicle charging technologies and their integration with the main grid.

2. Integration of plug-in electric vehicles and RES Technologies in smart grid scenario

The existing electric power system is facing a transition phase from a centralized configuration, mainly based on the use of thermal power plants, towards a distributed architecture, which is characterized by an increasing diffusion of energy generation systems based on Renewable Energy Sources (RESs). In fact, the use of RESs, such as solar and wind energy, presents the main advantage of

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Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.
doi:10.1016/j.egypro.2017.03.666

reducing green house gases emissions and fossil fuel consumption. Unfortunately, these kinds of energy sources are not dispatchable and their natural uncertainty and variability are considered important issues to be faced in order to obtain their efficient integration with the main grid. In particular, electric power fluctuations related to solar generation systems could be preliminarily evaluated since the movement of the sun is known, but the unpredictable presence of clouds and/or other causes of mismatch can limit the generated power of the PV systems with very rapid changes. Power fluctuations in wind generation systems are generally slower but less predictable, in comparison with PV generation systems, with strong increases of the generated electric power in correspondence of wind gusts [1].

The above issues can be properly addressed in a smart grid scenario, where energy storage technologies play an important role in supporting the integration of Plug-in Electric Vehicles (PEVs) and RESs with the main grid. In fact, PEVs battery packs can support the main grid by storing the exceeding electric energy produced by RESs, during the low power demand phases. In this case, the electric power flow is supplied by the main grid towards vehicles on charge, which are enabled to participate energy market with frequency and voltage regulation services. Moreover, the electric energy stored in PEVs battery packs can be used to support the main grid with ancillary services, also referred as vehicle to grid (V2G) services, playing also the role of efficient peak power and spinning reserves [2]. In this last case, PEVs interact with the main grid both as power consumers and as distributed generation units and for this reason the use of on-board or off-board bidirectional battery chargers is required. Bidirectional V2G systems can support the grid with higher quality ancillary services. Unfortunately, the economic benefits of this mutual interaction between the grid and PEVs are reduced by the need to involve specific safety protection systems, such as anti-islanding protections, and the higher cost of power electronics devices related to bidirectional charging systems [3]. In addition, ancillary services supplied by a single vehicle are often negligible, in terms of available electric power and energy, in comparison with the needs of the main electric grid. Finally, continuous battery cycling required by V2G operations strongly affects the battery durability, as a function of the depth of discharge of each cycle, with negative consequences on owners' acceptance towards V2G operations [4].

Higher benefits can be obtained when PEVs are not considered as single entities and are grouped on the base of an aggregation logic, which allows supplying the main grid with high power bidirectional V2G services. In fact, in the smart grid context, PEVs can be managed with either direct or aggregative power and communication architecture [5]. The main scheme of a direct power and communication architecture is reported in Figure 1a.

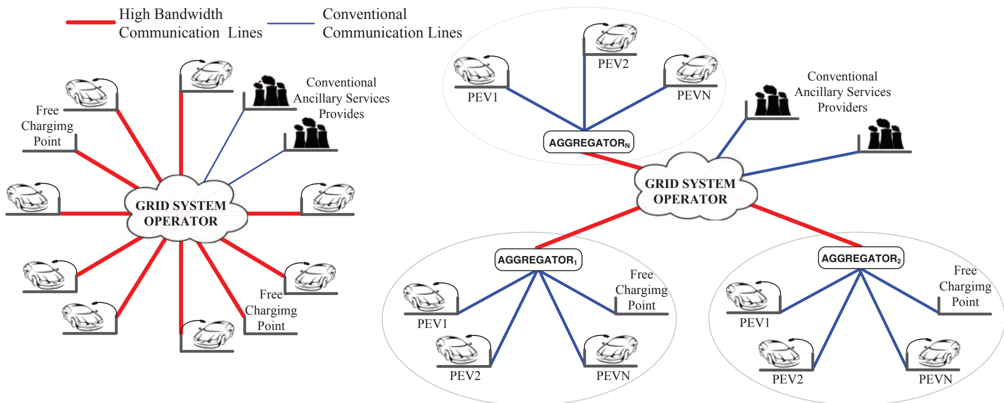


Fig. 1. PEVs charging and communication architectures. (a) Direct V2G Architecture (b) Aggregative Indirect V2G Architecture

In particular, this architecture is based on a direct communication scheme between the Grid System Operator (GSO) and vehicles on charge. In this scheme, the GSO controls each vehicle as a single deterministic power source, through direct communication lines. In addition, the vehicle owner can trade with the GSO for ancillary services, whose availability ends when the vehicle leaves its charging point. The direct architecture represents a very simple scheme for the management of V2G operations but unfortunately it results affected by recognized technological issues. In fact, the continuous interactions among GSO and vehicles on charge require a wide diffusion of high bandwidth communication lines, which are required by the geographically distributed nature of V2G services. In addition, long-terms evaluations need to take into account, on the base of possible market penetration scenarios, the expected increase in the number of vehicles, which are engaged and disengaged for simultaneous interactions with the GSO [6]. In this context the GSO is required to constantly update information about contract status, connection status, owner requirements and state-of-charge for each PEV.

In order to solve the main issues related to the direct architecture, an aggregative indirect V2G architecture is proposed in the literature [5]. The main scheme of this architecture is reported in Figure 1b. In this case, PEVs connected to the main grid are grouped on the base of an aggregative logic and act as virtual power plants (VPPs) during bidirectional V2G operations. Each aggregator works at an intermediate level interposed between the GSO and PEVs on charge. On the base of this scheme, an aggregator receives directly from the GSO specific requests for ancillary services, using conventional communication lines. Then, through high bandwidth communication lines, the aggregator directly controls the V2G operations of the available vehicles in charge. In this way the GSO can take advantage of high power ancillary services without affecting vehicle owners habits and PEVs battery pack durability. In fact, each vehicle can contributes to V2G operations involving low amount of electric energy from its battery pack reducing in this way the related depth of discharge. The aggregative architecture presents further advantages in terms of reliability and availability of ancillary services provided by the aggregator, which in this case, can be considered by the GSO as a conventional provider of ancillary service. At the same time the communications infrastructure related to the aggregative architecture is simplified since the communication between GSO and aggregator can be performed using conventional communication lines. For this reason indirect aggregative architecture is generally considered modular and extensible since it can easily support an increasing number of PEVs with an increased number of aggregators [5] [7].

3. Power Architectures to support electric and hybrid vehicle charging operations

The battery pack in PEVs represents one of the most critical components of their structure. Its energy density, charging time, lifespan and cost are currently driving the developments in EV technology. This section will present a brief discussion on current battery charging architectures. They can be classified depending on different factors such as structure, power rating, charging times, type of connection, location and so on.

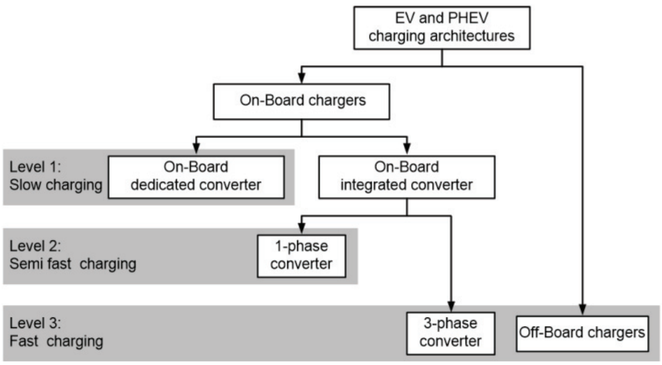
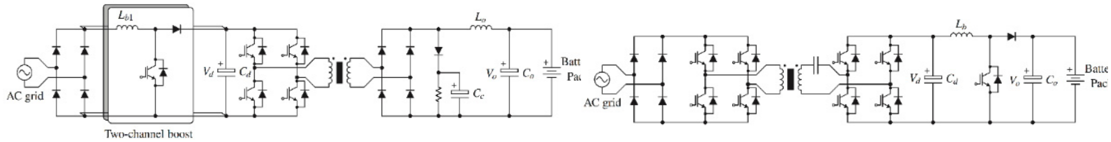


Fig. 2. Classification for EV and PHEV charging architectures.

Currently the most accepted classification is presented in Fig. 2. It can be seen that the different charging technologies are categorized according their power levels [8], leading three main groups: level 1 for powers under 1.92 kW, level 2 up to 19.2 kW and level 3 for chargers that deliver power over 20 kW. Additionally, depending on the nature of the supply needed, the chargers can be either AC or DC. Furthermore, depending on the location of the charger component or stages, they are also divided between onboard or off-board chargers. The location of the charger is strongly related with the nature of the charging process involved: an on-board charger will provide flexibility, simplicity and minimal external equipment besides the power outlet, while an off-board charger is able to reduce the charging times with no restrictions on its size, volume or weight. As depicted in Fig. 2, different configurations can be evaluated, the main configurations present in the literature will be briefly discussed in the following sections.

Typically, level I solutions provide a flexible and simple way of recharging the battery. They use a dedicated power converter that performs the battery charging tasks [8,9]. These converters feature a two-stage power conversion structure: an AC/DC stage that generates an intermediate DC voltage, while generating low distortion currents at unity power factor, and a DC/DC stage which generates the battery charging current. These chargers also include galvanic isolation toward the utility, in order to comply with safety standards [8]; some examples are shown in Fig. 3.

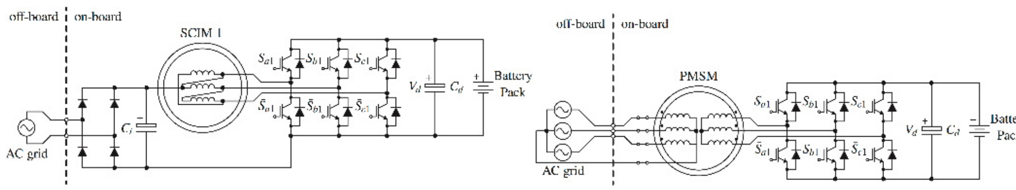


(a) (b)

Fig. 3. Examples of two-stage on-board chargers with HF galvanic isolation and dedicated charging converter. (a) Full-bridge converter with interleaved boost PFC. (b) Uncontrolled LLC resonant converter with low-voltage boost PFC.

The converters presented in Fig. 4 exhibit a common feature: the galvanic isolation achieved using high-frequency transformers instead of a low-frequency ones. The reason for this is the lighter weight and reduced volume of HF solutions. Nevertheless, HF isolation requires more power converter stages through which all the power is transmitted, resulting in additional switching, conduction and magnetic losses reducing the converter efficiency.

Following with the classification, level II solutions offer shorter charging times at the expenses of a larger and bulkier battery charger. This category of chargers extends the power ratings based on the following premise: under normal regimen, the driving and battery charging does not happen simultaneously (with the exception of regenerative braking), which enables to use part or entirely the power converter of the drive as the battery charger power converter. Depending on the level of integration, this category is further divided in partially and fully integrated battery chargers.



(a) (b)

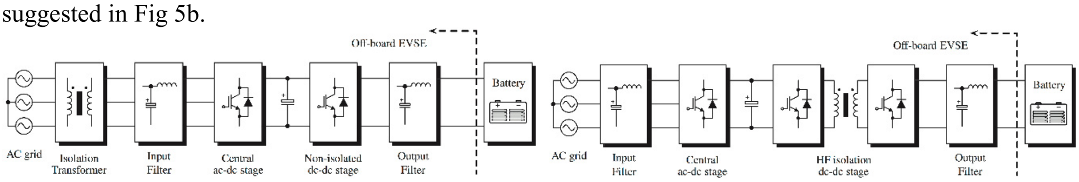
Fig. 4. Integrated on-board chargers using the drive inverter and motor windings. (a) Based on a SCIM and (b) Isolated IPMSM.

Fully integrated or combined chargers use the windings of the motor as a part of the charging circuit together with the traction inverter. A couple of examples can be observed in Fig. 4, and the main objective is the minimal addition of external elements to enable the reconfiguration of the circuit.

Naturally, given the fact that the power train is designed for higher power ratings, these chargers allow to further reduce the charging times without excessively modifying the weight of the vehicle.

A different approach for enabling the refuelling of the PEVs is through the use of specialized off-board infrastructure dedicated to recharge their batteries. The result is offsets the cost, weigh and volume from the car to the electric vehicle supply equipment, which is responsible to deliver power to the battery from the grid. This option also supports the widespread of PEVs, as the availability of a quick-charge stations throughout the city will provide flexibility and simplicity for the replenishing of the batteries. Moreover, this idea is supported by different studies, even in the scenario where fast charging is not the preferred method to recharge the batteries [10].

The general structure for off-board chargers is provided by Fig. 5 [11]. Regardless the architecture, these chargers consist of two energy conversion stages, an AC/DC stage that performs the grid integration and generates a regulated DC voltages, and a DC/DC stage that performs the current shaping to charge the batteries, as required by the vehicle BMS. Regarding the isolation stage, as it is displayed in Fig. 5a it could be included at the low frequency side using a transformer or in the DC/DC stage in the HF range as suggested in Fig 5b.



(a) (b)

Fig. 5. General structure of off-board battery charger: (a) LF isolation. (b) HF isolation.

Off-board chargers can be conceived in the shape of charging stations following the implementation of conventional gas filling stations. The structure of this charging station can either be with an AC bus, where each charging unit is fed by its independent AC/DC stage, or each unit connected to a common DC bus enabled by a single AC/DC stage with higher power ratings, as the configuration in Fig. 6. The latter option appears as the viable solution due to the nature of the loads, and also presents advantages in terms of cost, efficiency and size, as fewer conversion stages are needed [11]–[13]. Moreover, this structure facilitates the integration of distributed generation or energy storage systems [12,13]. Finally, this concept supports the widespread of fast charging throughout the city, as the reduction in the AC connections allows to strategically locate the charging stations and potentially large loads in the distribution system, facilitating the planning of the charging network and a sustainable shift into the new distribution system.

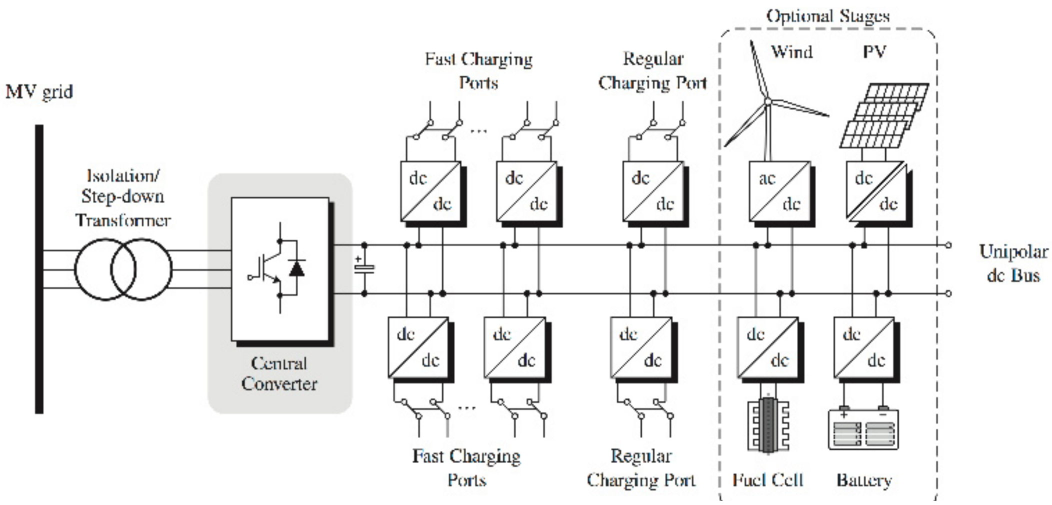


Fig. 6. Charging station with common DC bus.

4. Conclusions

In this paper an overview on charging architectures for the integration of sustainable mobility and distributed energy sources in the smart grid scenario is presented. In particular, the use of PEVs battery packs is proposed to support the main grid with ancillary services and for smoothing the natural power fluctuations of RESs. With this aim, different aggregation schemes have been analysed in order to optimize the V2G bidirectional operations in terms of communication with GSO, power supplied by vehicles battery packs and convenience for vehicle owners.

5. Copyright

Acknowledgements

This work has been supported by the Horizon 2020 Project REPLICATE (REnaissance of PLaces with Innovative Citizenship And TEchnology) number: 691735). The authors gratefully acknowledge Mr. Antonio Rossi, technician of Istituto Motori, for his cooperation in drawing the figure of this paper.

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Biography

Ottorino Veneri graduated and awarded his PhD in Electrical Engineering by the University of Naples Federico II. Since 2002 he works as a researcher with the Istituto Motori of the National Research Council of Italy. His main fields of interest are the electric drives for transportation systems, electric energy converters, electric energy storage systems and power sources with hydrogen fuel cells.