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Review on plug-in electric vehicle charging architectures integrated with distributed energy sources for sustainable mobility

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HIGHLIGHTS

- Outlook of PEV charging infrastructures.
- Integration of electric and hybrid mobility with distributed energy sources plants.
- Traditional and innovative power electronics architectures.
- Inductive and conductive PEV charging systems.
- PEV battery management.

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ABSTRACT

In this review, the aim is to present a complete outlook for innovative charging infrastructures. In a real smart grid scenario, these infrastructures are candidates to support the integration of electric and hybrid mobility with distributed energy sources. In this paper, at the outset, an analysis of the scientific and technical literature about main international standards and classifications has been provided. Also taken into consideration in this analysis are the expected challenges related to charging technologies for electric and plug-in hybrid vehicles, giving specific details on current and possible future trends for both stationary and dynamic inductive charging systems. In particular, for each charging level, traditional and more innovative power electronic architectures—equipped with the new technologies that support both slow and fast conductive charging operations for the new-generation road vehicle–have been reported, described and analysed in detail. The analysis has been conducted through a comparison of power architectures, in terms of efficiency, scalability and charging power/time of the vehicle battery packs. Specific attention has also been devoted to off-board DC fast-charging architectures, which play a fundamental role in the integration of stationary energy storage systems and renewable energy sources with the main grid. Finally, in this review, a wide range of the most interesting applications, technical experiences and international pilot projects have been summarized and discussed, with specific references to the new technologies mentioned above. The overview reported in this paper highlights the importance of a proper charging infrastructure, in combination with next generation energy storage technologies, to support the large-scale diffusion of electric and plug-in hybrid vehicles.

1. Introduction

The huge consumption of liquid fossil fuels in transportation and energy generation sectors is considered to be one of the main causes for the recent increase in atmospheric concentrations of greenhouse gases; in particular, that of carbon dioxide. Moreover, the large demand for fossil fuels—mainly due to the worldwide growth in the number of road vehicles and electric utilities—is expected to increase continually in the next years [1,2]. Even though recent advancements in internal combustion engine technologies—encouraged by new international legislations that are enforceable—have motivated improvements in vehicle conversion efficiencies and tailpipe emissions, environmental issues still persist, with drastic effects on earth's atmosphere and human health [3]. Consequently, the long awaited transition towards sustainable transportation systems–supported by the efficient integration of renewable energy sources with the main grid—is becoming an

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important challenge to be addressed from the technical and scientific point of view.

The use of electric drives for vehicle propulsion systems represents an attractive solution, which involves various advantages such as the high values of well-to-wheel conversion efficiency and the possibility to operate in urban areas in full-electric mode—without local exhaust emissions. Encouraged by the above advantages, the automotive industry commercially introduced the first generation of Hybrid Electric Vehicles in 1997 (HEV) [4]. These vehicles were characterized by a propulsion system based on an Internal Combustion Engine (ICE), which works in combination with an electric drive with positive consequences related to vehicle performance, fuel consumption and environmental impact. Nowadays, HEV represent mature technology and have been adopted by a conspicuous number of users in both the private and the corporate sector. Many HEV with various configurations are now available on the market and can be classified on the basis of either hybridization degree, which is related to the ratio between the ICE and electric drive power, or propulsion system architecture (parallel, serial, parallel-serial, power-split, etc.) [5,6]. Recent developments in battery technologies have supported the spread of a new generation of hybrid electric vehicles on the market, characterized by the capability to cover long distances in full-electric mode. In this case, the vehicle battery pack can be recharged by using the energy coming from the main grid, by connecting the vehicle to an external charging plug using a specific connector. For this reason, these vehicles are also called Plug-in Hybrid Electric Vehicles (PHEV) [7]. A good alternative, especially for urban use, is represented by Battery Electric Vehicles (BEV or EV), where power to the electric drive is supplied from the on-board battery pack. In this case, the ICE is completely excluded, as the large battery pack in the vehicle can ensure a daily travel range of about 150 km. Such vehicles can be connected to specific charging points and recharged from the main grid using connectors. Therefore, PHEV and BEV are both generally referred to as Plug-in Electric Vehicles (PEV) [6]. Further details on hybrid and electric vehicles classification are widely available in the scientific literature [8–11].

In fact, the large-scale spread of PEV in the automotive market is still affected by battery technologies and the charging infrastructure. A slight increase in the demand for PEV in the private and corporate sectors has been supported by new lithium based energy storage systems [12,13]. In fact, lithium compounds have allowed storage system technology to reach high values of energy and power densities, with positive effects on PEV performance in terms of acceleration and daily travel range in full electric mode. The above battery technologies can be charged during the night through private low-power charging equipment, with charging times of up to 8 h. This type of operation presents a low power requirement for the main grid and therefore can be considered generally acceptable for urban mobility. On the other hand, the autonomy of PEV when compared with traditional vehicles based on internal combustion engines, is still considered, by a large section of the users, insufficient to cope with the well-known 'range anxiety' [14,15]. For this reason, the capillary diffusion of a proper charging infrastructure would be required in order to encourage the use of PEV for travel paths as well, which are longer than the typical daily urban paths. This infrastructure should support vehicle owners with commonly available fast or semi-fast charging stations or with mobile wireless power transfer charging systems during their journey. This means that high-power requirements, involving a large number of simultaneous PEV charging operations, should be addressed through the existing electric network. In a smart grid scenario, a PEV would be charged in an efficient and clean way through the intelligent integration of renewable energy sources and stationary energy storage systems. This scenario would support the main grid in its interaction with the plug-in sustainable mobility. In this case, the efficient integration of PEV is obtained through the direct or indirect interaction between the main grid and on-board or off-board charging devices.

A large number of review papers have addressed the above topics. In the first group of papers [7–11], an overview of the main technologies and issues related to PEV propulsion systems have been presented. The aim of these papers is the evaluation of the most promising on-board energy management/control strategies, associated with different power-train configurations, adopted by the main car manufacturers. Smart charging approaches and vehicle-to-grid operations are analysed in detail in [16–18], with particular reference to the improvement of grid safety and reliability through the smart integration of PEV with the main grid. Other papers focus on traditional and innovative power conversion architectures for PEV battery-charging devices. In particular, paper [19] presents an overview of the main solutions adopted for on-board battery charging devices, which are generally suitable for low and medium power charging operations in a PEV. In [20], Yilmaz et al. report a review of the most used topologies and standards for PEV battery chargers characterized by different peak power, with details on both uni-directional and bidirectional solutions.

In this context, this manuscript is aimed at providing a complete and updated analysis on charging architectures for PEV, with reference to conductive and inductive charging technologies. This analysis is particularly focused on innovative power conversion architectures, based on the use of modular multi-level converters, which allow the optimal integration of PEV with the main grid through the efficient use of distributed energy storage systems and renewable energy sources. The presented topologies have been analysed and compared in terms of scalability, efficiency and peak charging power, taking into account their impact on the main grid in terms of power quality. The review ends with a description of the main results related to worldwide applications of the above charging technologies in the context of pilot research projects funded by public or private institutions.

2. Main standards for charging operations of PEV

The main elements of PEV charging architectures are represented by the power grid, the communication network, and PEV charging systems. The power grid supplies electric power to charge PEV. For this reason, a large deployment of PEV involves preliminary evaluations of the impacts that vehicle charging operations may have on the power grid and the identification of the best charging strategies to be adopted. In this regard, a communication network is required to support the efficient integration of PEV with the main grid on the basis of agent and multi-agent aggregation schemes [21]. PEV Charging systems are devoted to the control and management of vehicle charging operations, with smart interactions with both vehicle Battery Management Systems (BMS) and other centralized control systems at a higher hierarchical level. The development of power electronic technologies related to PEV charging systems can play a key role in reducing both vehicle charging times and the impact of charging operations on the main grid, which are still considered the main technical bottlenecks for a large-scale proliferation of sustainable mobility [22].

A high-level classification of PEV charging systems is based on the presence or absence of wires for the electric power transfer between vehicles and charging units. On the basis of this classification, PEV charging systems can be classified as either conductive or wireless PEV chargers. The second group is also referred to as inductive chargers, because in this case the electric power is transferred through magnetic fields by using inductive coupling

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