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Integrated photovoltaic-grid dc fast charging system for electric vehicle: A review of the architecture and control

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A R T I C L E I N F O

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A B S T R A C T

The fast charger for electric vehicle (EV) is a complex system that incorporates numerous interconnected subsystems. The interactions among these subsystems require a holistic understanding of the system architecture, control, power electronics, and their overall interaction with the electrical grid system. This review paper presents important aspects of a PV-grid integrated dc fast charger—with a special focus on the charging system components, architecture, operational modes, and control. These include the interaction between the PV power source, grid electricity, energy storage unit (ESU) and power electronics for the chargers. A considerable amount of discussion is also dedicated to battery management systems (BMS) and their mutual interactions in the control processes. For the power electronics, the paper evaluates soft switching non-isolated dc-to-dc power converter topologies that can be possibly used as future EV chargers. In addition to these, a brief discussion on the impact of the PV-grid charging on the ac grid and distribution system and their remedial measures are presented. Furthermore, the challenges in regard to the vehicle to grid (V2G) concept are also described. It is envisaged that the information provided in this paper would be useful as a one-stop document for engineers, researchers and others who require information related to the dc fast charging of EV that incorporates a renewable energy source.

1. Introduction

The expected growth of electric vehicle market (EV) mandates a corresponding development in the charging facilities [1,2]. Next to the battery [3,4], the availability and reliability of chargers are of utmost concern. Efforts are being made to enhance the charger efficiency, to make it more versatile and to reduce the charging cost. Despite the encouraging indicators, implementing high power, fast charging facilities is not trivial. In [5–8], the authors describe the technological challenges to integrating the electrical grid into the EV chargers. The uncontrolled and random charging pattern may lead to voltage deviation, distribution losses, and degradation in power quality. Furthermore, the issue of reduced transformer lifetime due to overload and instability need to be addressed.

Recently, there are growing interests in utilizing Renewable Energy (RE) as a secondary energy source for the charger. Most possible RE sources include the wind, biomass and solar [9]. However, solar photovoltaic is a more feasible solution, especially for day-time charging. With the continuous downward trend in the price of the PV modules, this proposal is becoming attractive—as evident from numerous recent publications [2,10–13]. A PV system is easy to set-up, and is almost maintenance free [14]. This prospect is further enhanced by the improvement in power conversion technologies and installation practices [15–17]. Furthermore, since the charging is carried out during the peak demand period (daytime)—where the tariff is normally at its highest [18], the economic returns can be substantial [19]. M. Brenna et. al.[20] evaluate the benefits of integrating PV into the charging system, while in [11,13,21–24] its effectiveness in the smart grid

Abbreviations: BMS, Battery management system; CAN, Controller area network; CB, Circuit breaker; CC, Constant current; CCS, Central control system; CMS, Charger management system; CV, Constant voltage; DSP, Digital signal processor; ESU, Energy storage unit; EV, Electric vehicle; EVMS, Electric vehicle management system; EVSE, Electric vehicle supply equipment; GA, Genetic algorithm; MPP, Maximum power point; MPPT, Maximum power point tracking; PLC, Power line carrier; P & O, Perturb and observe; PQ, Power quality; RE, Renewable energy; SAE, Society of automotive engineers; SG, Smart grid; SOC, State of charge; SOH, State of health; OCV, Open circuit voltage; V2G, Vehicle to grid; ZVS, Zero voltage switching; ZCS, Zero current switching; ZVT, Zero voltage transition

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Nomenclature

Symbol unit description

v_{PV}	Volt (V) PV voltage
i_{PV}	Ampere (A) PV current
v_{max}	Volt (V) Max. charging voltage
i_{max}	Ampere (A) Max. charging current
S, M	- Power switch
C	Farad (F) Capacitance
L	Henry (H) Inductance
R	Ohm (Ω) Resistance
T_S	Degree celsius Safe operating temperature
V_S	Volt (V) Safe operating voltage

environment is discussed. In [25], the authors investigate various architectures for the PV-Grid system, incorporating of either ac or dc buses. On the converters, the N. Naghizadeh and Y. Du et.al.[26,27] present a review on the topologies suitable for integrated PV-grid charger. The main focuses are the bi-directional dc-dc or dc-ac converters, coupled with the maximum power point tracking algorithms. The charger operational modes and its optimization are discussed in [28–30]. In addition, the merits of employing energy storage units (ESU) to reduce the negative effect on the grid are discussed in [29,31,32]. The work is further enhanced and supported with detailed system modeling, simulation and experimental evidence presented in [30].

The brief overview above provides a flavor on the issues related to the integration of PV into the conventional grid for the EV charging. Evidently, it consists of several sub-systems that interact with each other in a complex way. The literature that addresses these issues can be grouped into several categories, namely 1) charger topologies, 2) energy management and 3) system optimization. Although there exist several excellent review papers [2,11,12,33] that summarize the recent trends, they tend to focus on specific aspects of the system. For example, in [2], the emphasis is on the isolated and non-isolated dc chargers for PV-grid charging schemes. F. Mwasilu et. al.[12] review the EV charging infrastructures in the smart grid context, while [33] presents the optimization of the vehicle-to-grid (V2G) integration. On the other hand, the work in [11] details the cost minimization, efficiency maximization and emission reduction of the PV-grid system.

Despite these works, there appears to be an absence of comprehensive review papers that combine the stated issues relating to the PV-grid integrated charging. Besides, so far there is no paper that covers the issues relating to the PV-grid integrated dc fast charging system for EV. Thus, this paper presents a review of the architecture of such a system that incorporates the battery management system (BMS) and charger management system (CMS) as part of the control. The functions of BMS for the state of charge (SOC) estimation, battery equalization, cell balancing and its inter-relation with the charging management system (CMS) are covered. Besides, a short discussion on renewable energy integration with the EV charging is presented. In addition, the paper evaluates the dc charger module, focusing on the soft switching bidirectional non-isolated topologies. For completeness, the impact of charging on the distribution grid, system assets, and power quality are discussed. An insight into the future of the vehicle-to-grid (V2G) is also presented.

2. System of common use and the charging standards

Large scale penetration of the EV into car market is highly dependent on the widespread and successful implementation of the charging infrastructures [16]. Often, the selection of charging power level is an optimization between the cost of infrastructure and the charging time. There are two main categories of the EV charger: the ac and dc types, as shown in Table 1 [1]. Furthermore, there are three main worldwide bodies that are competing to become the *de-facto* standard for the EV battery charging: they are the IEC, CHAdeMO, and SAE. In addition, Tesla Motor also proposes its own charging standard for its EV.

The charging time for the EV depends on three factors, namely size of the battery pack, power rating of the charger, and the number of EV that are connected to the charger at that instant. The *ac Level 1* is an on-board charging facility, derived from conventional 120 V ac outlets. It requires no extra setup and thus the charging can be done conveniently (normally overnight) at home. However, due to the size, weight, and thermal constraints, the *Level 1* charging current is very much limited, hence the long charging time. The majority of public charging stations in the US and elsewhere are the *ac Level 2*—powered by a 240 V ac outlet. It requires a dedicated setup at charging sites due to its voltage rating and higher power handling capability. The *ac Level 3* has even higher power ratings to ensure fast, secure and convenient charging as mostly preferred by EV owners. However, *ac Level 3* charging is yet to be implemented. As the battery pack size and the number of EV on the road is increasing day by day, the only feasible way to reduce the charging time is to increase the power rating of the chargers. The *dc fast charger* is the most promising candidate to fulfil this requirement; hence the widespread installation, particularly at commercial charging stations.

The dc fast charging is offered by the IEC CHAdeMO, SAE J1772 Combo and Tesla-S supercharger. The CHAdeMO is a conductive dc fast charger that allows up to 200 A charging at 50 kW. To establish secure communication between electric vehicle management system (EVMS) and charger control units, controller area network (CAN) protocol is applied. From the smart grid (SG) context, the CHAdeMO supports bidirectional power flow for the future vehicle to grid (V2G) or vehicle to home (V2H) applications. The SAE J1772 Combo 1 and 2 is a combined charging standard developed by the Society of Automotive Engineers (SAE). It specifies the physical, electrical and functional requirements to support the *ac Level* 1, 2, 3 and dc fast charging. The Combo 1 (or alternatively known as IEC Type 1) is commonly used in

Table 1
EV charging standards.

Level	Max power rating (kW)	Max ampere rating (A)
IEC Standard		
AC Charging		
ac Level 1	4 –7.5	16
ac Level 2	8 –15	32
ac Level 3	60 –120	250
DC Charging		
dc Fast Charging	100 –200	400
SAE Standard		
AC Charging		
ac Level 1	2	16
ac Level 2	20	80
ac Level 3	Above 20	–
DC Charging		
dc Level 1	40	80
dc Level 2	90	200
dc Level 3	240)	400
CHAdeMO		
dc Fast Charging	62.5	125