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ECONOMIC ASSESSMENT OF A PUBLIC DC CHARGING STATION FOR ELECTRIC VEHICLES WITH LOAD SHIFT CAPABILITY

J. G. Pinto*, Vítor Monteiro, Delfim Pedrosa and João L. Afonso

Centro ALGORITMI – University of Minho, Guimarães – Portugal

* Corresponding author: gabriel.pinto@algoritmi.uminho.pt, University of Minho, Campus de Azurém, 4800-058 Guimarães, Portugal.

KEYWORDS
EV DC Fast Charging; Energy Storage System; Load Shift.

ABSTRACT

This paper presents a new concept of public DC fast charging station for Electric Vehicles (EVs) with load shift capability and simplified interface with renewable energy sources. The key element of the proposed charging system consists in an Energy Storage System (ESS) composed by reused electrochemical batteries from EVs. In the proposed system the energy storage capability is used to smooth the intermittent power demand of fast charging systems for EV batteries, present in public charging stations, and also contributes to the stability of the electrical power grid. When integrated in a Smart Grid, the proposed system may even return some of the energy stored in the EVs batteries back to the power grid, always when it is necessary, in order to improve the power grid operation. In addition to these technical advantages, the proposed topology also presents some interesting economic benefits that are analyzed along the paper.

INTRODUCTION

Nowadays, the energy efficiency is a top priority, boosted by a major concern with climatic changes and by the soaring oil prices in countries that have a large dependency of imported fossil fuels. Aiming to improve the energy efficiency in the transportation sector, the electric mobility concept through Electric Vehicles (EVs) arises, and must include technological developments in different areas, such as Power Electronics, Mechanics, and Information and Communication Technology (ICT) (Rajashekara, 2013)(Emadi, 2008). Nevertheless, the power grids were not designed for this new type of loads, and the impact caused by the proliferation of EVs cannot be neglected (Raghavan, 2012)(Shao, 2012). The integration of EVs in the power grids will be a fundamental contribution to the future Smart Grids [5], which are not characterized as a single technology or device, but rather as a vision of a distributed electrical system, supported by reference technologies, as power electronics devices, Distributed Generation (DG) from renewable energy resources, Energy Storage Systems (ESS), Advanced Metering Infrastructures (AMI), and ICT (Güngör, 2011).

Regarding to the slow charging of the EVs batteries (modes 1, 2, and 3 of the IEC 61851-1 standard) some authors propose the use of bidirectional on-board chargers instead of the conventional unidirectional chargers, enabling the Vehicle-to-Grid (V2G) mode of operation, which allows sending part of the stored energy back to the power grid (Monteiro, 2010). With respect to DC fast chargers (off-board chargers, Mode 4 of the IEC 61851-1 standard) it is usual the use an AC-DC together with a DC-DC converter. Typical topologies for these chargers are high-power twelve pulse diode rectifier followed by a buck type converter (Byrne-Finley, 2011), as well as Power Factor Correction (PFC) topologies connected in parallel (Soeiro, 2012), or three-phase active rectifiers followed by buck type DC-DC converter (Krasselt, 2015). Although the IEC 61851-1 Mode 4 charging mode allows charging with DC currents up to 400 A, which for a battery pack with 400 V corresponds to a power of 160 kW, the fast chargers currently available do not exceed 50 kW at 400 V (Efacec, 2008). The time required to fast charge the batteries of the EVs varies from one vehicle to another, and is essentially dependent of the battery capacity (Ah) and its State-of-Charge, however it usually does not exceed 30 or 40 minutes. In this way, the simultaneous fast charging of a large number of EVs represents a significant oscillation in the power demand from the electrical grid that can be problematic, especially in weak power systems, like islands or remote villages (Monteiro, 2016).

With the increasing number of charging and discharging cycles, the performance of the batteries of an EV reduces over the time, and consequently, the autonomy of the vehicle decreases, and thus it is necessary to carry out the battery pack replacement. However, these batteries may still be useful for applications where the charge density is not so important. Considering that in average the batteries of the EVs have a charge density of about 70% of the initial value after 10 years of use (ABB, 2010), when it is necessary to replace the batteries, they can still be reused in an Energy Storage

System (ESS) with benefits to the power grid. This paper proposes and makes the economic assessment of a public DC charging station for electric vehicles which uses batteries recycled from EVs with load shift purposes.
The rest of the paper is organized as follows. Section II presents the details of the DC fast charging station for EVs. Section III presents the load shift control scheme for the DC fast charging station. Section IV presents the economic assessment of the DC charging station. Finally, Section V presents the main conclusions of the work.

PROPOSED DC CHARGING STATION FOR EVs

Conventional DC fast battery chargers (off-board chargers, Mode 4 of the IEC 61851-1 standard) are connected to the three-phase low voltage AC power grid (400 V / 50 Hz in Europe) and uses a two-stage AC-DC power converter to interface the EV batteries. The first stage converts the AC voltages of the power grid into a DC voltage, and the second stage adapts the voltage produced by the first stage to the batteries voltage. With this power converter it is possible to perform the battery charging in a controlled way respecting the battery limits and integrity. A public charging station based in this type of DC fast battery chargers will be composed of various units connected to the AC power grid. Figure 1 shows the block diagram of a public fast charging station based in conventional AC-DC chargers. In this figure it is possible to see the usual substation transformer and a set of EV DC fast charging posts. To allow a more accurate comparison with the proposed system, the charging station includes a renewable energy source that interfaces the power grid trough a two-stage DC-AC power converter. It is important to highlight that all the power electronics converters operate with balanced sinusoidal currents and unitary power factor in the AC side.

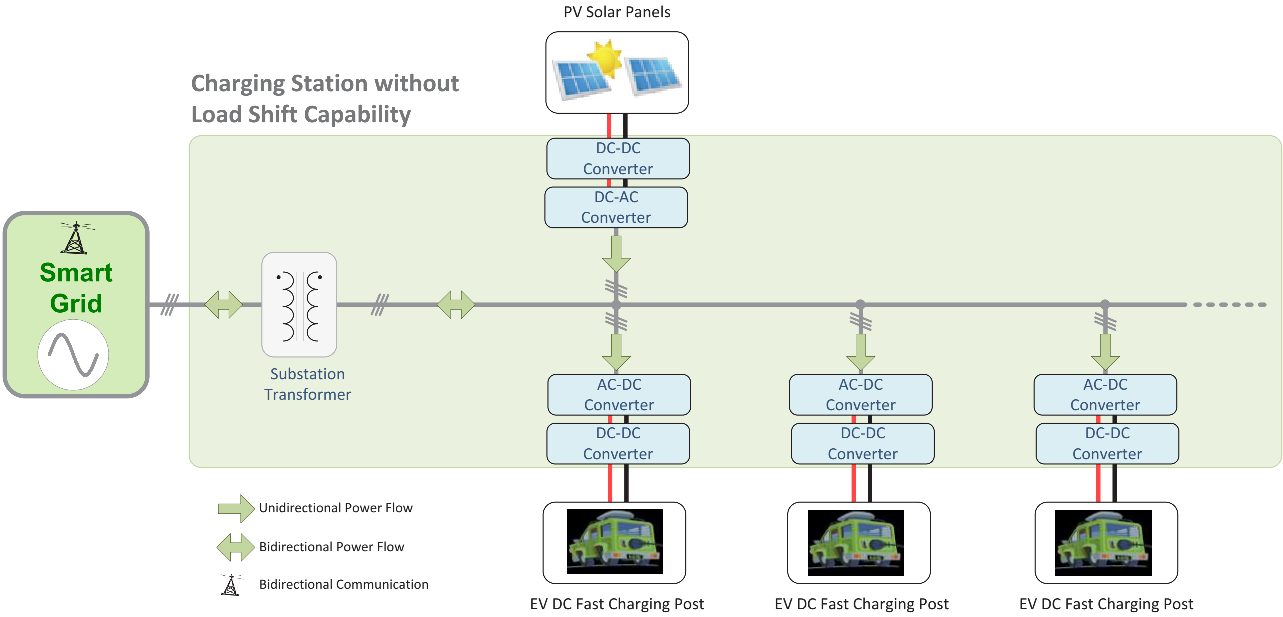


Figure 1: Block diagram of a public fast charging station based on conventional AC-DC chargers and renewable energy sources interface.

The proposed public DC fast charging station is presented in Figure 2 and consists on a set of power converters sharing the same DC-link, where are also connected a high capacity battery pack. Each one of the available DC charging posts is constituted by a simple DC-DC buck converter, representing a gain in terms of cost and efficiency when compared with the conventional DC fast charging systems, which are composed by one AC-DC converter followed by one DC-DC converter.
In the proposed architecture, the connection to the power grid is accomplished by a bidirectional converter. It is important to refer that the power rate of this converter is reduced, because it can operate in a continuous way or by long periods of time, while the DC-DC converters for the individual posts of the EVs battery chargers operate only during short periods of time. Another interesting feature of the proposed system is the easy integration of renewable energy sources, like solar photovoltaic panels, by using a simple DC-DC converter with a Maximum Power Point Tracking (MPPT) algorithm. This easiness of integration of renewable sources without need to use DC-AC converters makes it a more interesting investment in this kind of solutions, due to the gains in terms of performance and cost of the equipment, resulting in a reduction of payback period. It is important to highlight that the bidirectional AC-DC power converter operates with sinusoidal currents and unitary power factor in the AC side and absorbs from the power grid the required active power in an equilibrated way through the tree phases. These characteristics are very important to preserve the power quality of the electrical power grid.

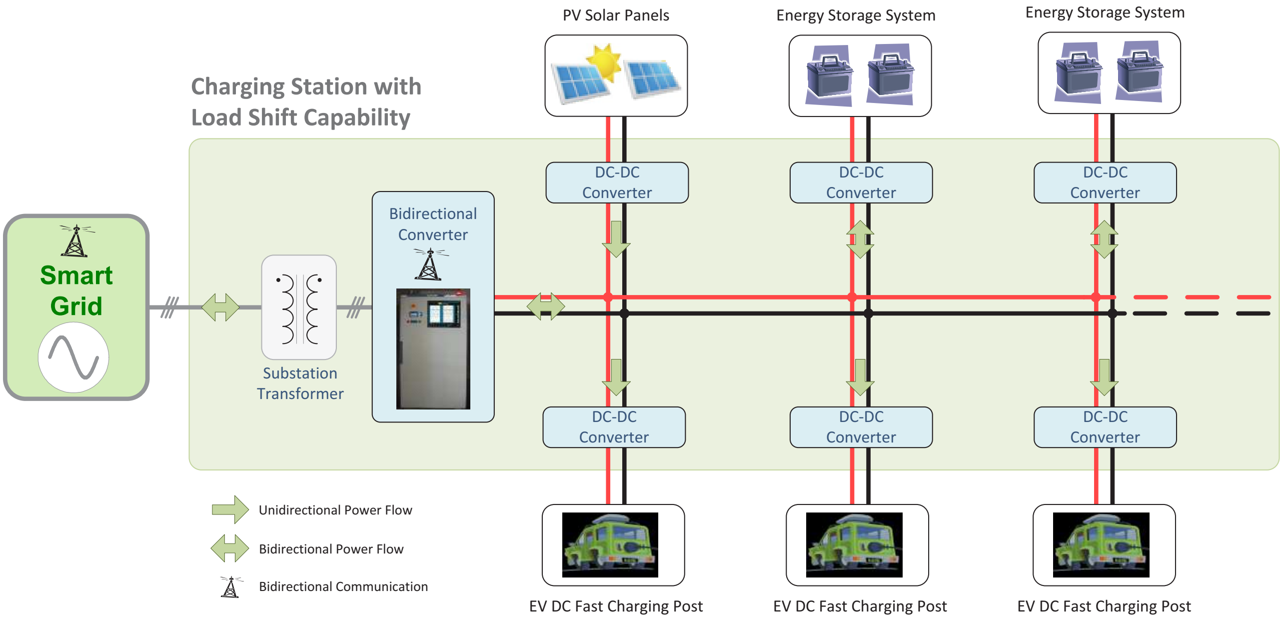


Figure 2: Block diagram of the proposed public DC fast charging station with load shift capability and renewable energy sources interface.

LOAD SHIFT CONTROL SCHEME

In order to achieve the maximum benefits from the proposed DC public charging station for EVs, the system controller must manage the energy storage to ensure available energy for all the clients and to reduce the consumption from the power grid during the peak periods were the cost of the energy is higher. In order to explain the revenues resulting from an optimized energy management it will be used a real scenario considering a charging station composed by a total of ten EV fast charging posts. Although the arrival of EVs to supply the batteries is theoretically random, there is usually a pattern of affluence of clients to the public charging station. Overnight there is little traffic and there are few customers. During the early hours of the morning the traffic increases, but in this time the inflow remains low because the EVs charged the battery, slowly at home during the night. From the mid-morning the influx of EVs increases significantly until the middle of the afternoon, and then beginning to decrease until the end of the day. Normally, the standard and total number of customers does not vary much during the days of work but changes significantly during the weekend. The analysis presented here focuses on a typical working day. On average, the public charging station serves a total of 200 EVs, which use the post for about 20 minutes to charge 15 kWh of energy. Figure 3 presents the typical charging schedule during a working day. This figure shows the number of fast charging posts that are in use in each 20 minutes time interval. It is possible to confirm that between the hours 2 PM and 5 PM almost all the fast charging posts are permanently in use.

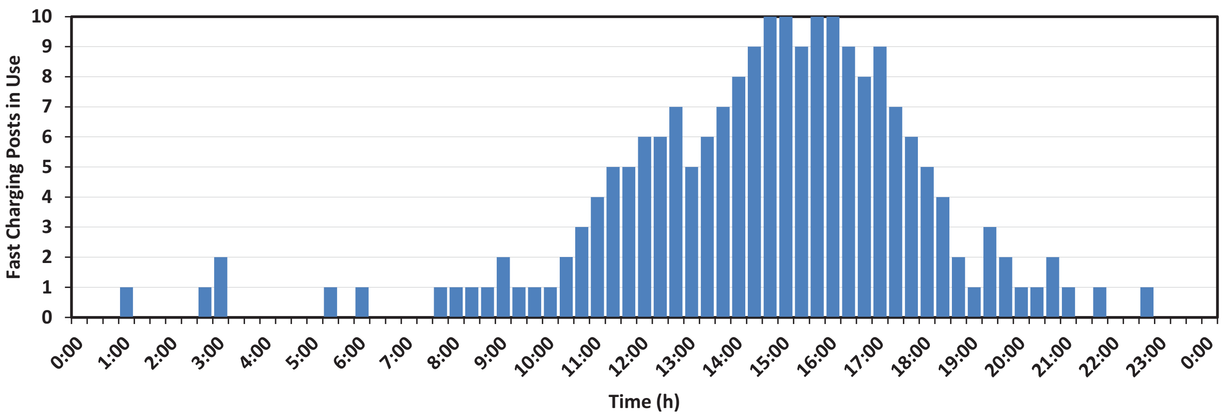


Figure 3: Number of charging posts in use in each 20 minutes interval during a typical working day.

Figure 4 presents the total active power and the energy absorbed by the public fast charging station along the day with and without the load shift management system. It is possible to see that, without the load shift, the total active power follows the EVs influx and reaching a maximum of 500 kW at 3 PM, and presenting very low values between 8 PM and 10 AM. During the day, the public charging station absorbs from the power grid a total energy of 3400 kWh. With the load shift manager in operation, the public charging station absorbs a constant power of 170 kW during all the time, with exception in the rush hour, when the charging station wittingly stops to absorb energy from the power grid due to the high energy price during this period. In terms of energy, it is possible to see that the stored energy in the load shift battery pack starts with a total amount of 500 kWh, reaches a maximum value of 2000 kWh, and finishes almost with the initial value of 500 kWh. With the load shift manager, the public charging station absorbs from the power grid a total energy of 3400 kWh, i.e., absorbs the same amount of energy with a maximum power 3 times lower.

To be able to work with the proposed load shift control scheme, the public charging station requires a minimum storage capacity of 2000 kWh. This is a considerable amount of energy, and even using batteries reused from EVs, it represents a high investment. However, the use of the proposed scheme presents a high number of benefits and allows some reduction in the installation costs in comparison with conventional fast chargers. A consumer with the presented profile is usually connected to the power grid in the medium voltage. With the proposed topology, the maximum power of the public charging station is 170 kW, instead of 500 kW, so the necessary power transformer will be much less expensive, and this is also true to the main switch board, switch breakers, electrical wires, etc. In addition, instead of using ten 50 kW AC-DC converters, one for each charging post, the proposed topology uses a single converter with a rated power of 170 kW. Besides, if there are renewable energy sources available, they can be integrated in the DC-link of the proposed topology by means of high efficient and less expensive DC-DC converters, in detriment of DC-DC plus DC-AC conventional converters necessary to interface the power grid. In terms of operation costs the load shift presents several advantages, since the contracted power is much lower, and so the cost with this parameter will be significantly reduced. Moreover, the charging station stops to consume in the rush hours, and therefore the total costs with energy will be lower, and also the cost with rush hour mean power will be drastically reduced. The main disadvantages are related with the energy storage efficiency and with the expenses related to the replacement of the storage batteries.

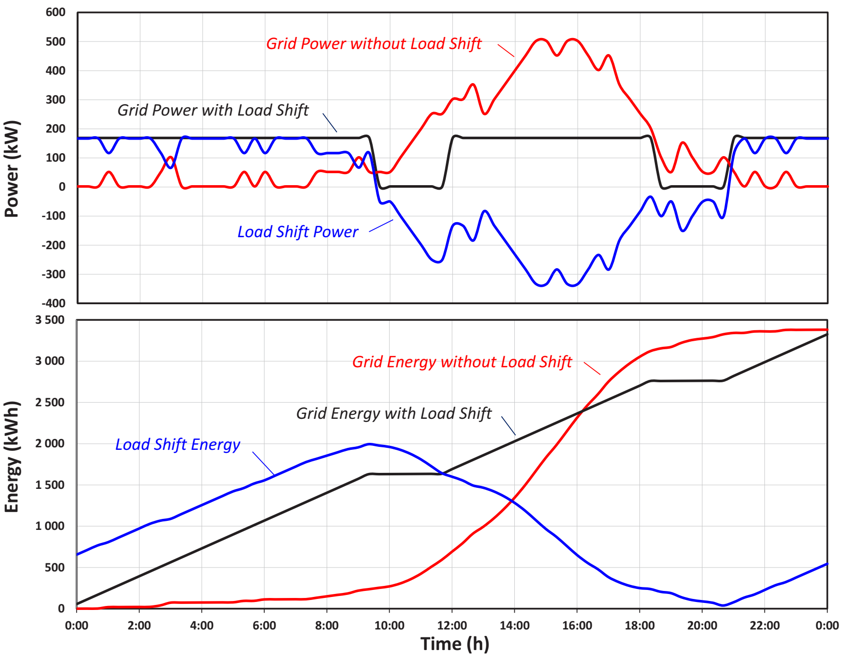


Figure 4: Power and energy consumed by the DC public charging station with and without the proposed load shift during a typical working day.

ECONOMIC ASSESSMENT OF THE DC CHARGING STATION

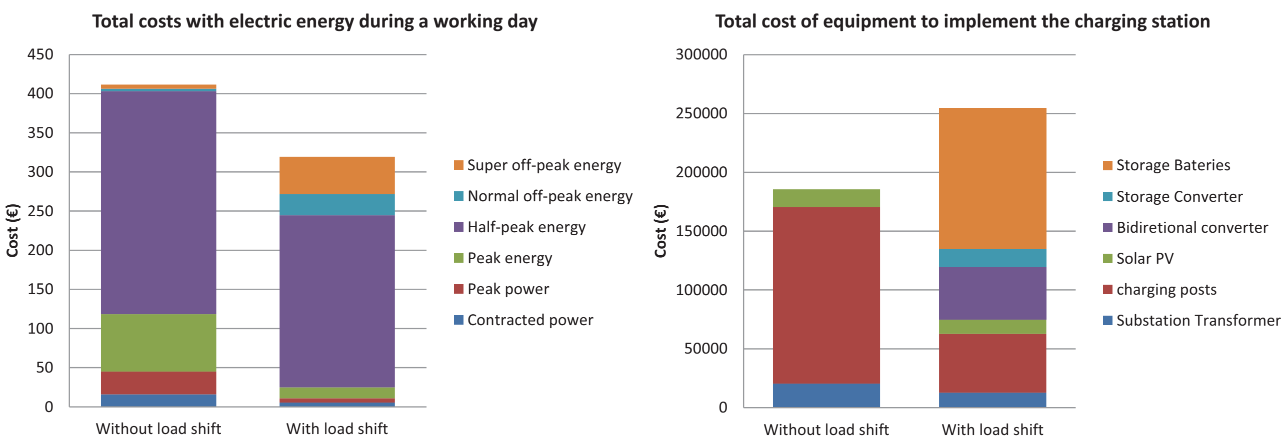
To evaluate the economic feasibility of the proposed public DC fast charging station it was established a comparison between the conventional and the proposed charging station considering the cost of energy and the cost of the equipment to implement the charging station. In terms of the energy cost are used real values from an actual electrical installation with characteristics very similar to the selected case study. In terms of equipment it is difficult to find the real price of all the components used in the charging station, therefore, some of the values are estimated taking into account the cost of similar equipment and the experience of the authors in terms of power electronics converters cost.

The cost of the electrical energy is not fixed but changes along the day and presenting different rates in four periods of time. Although energy cost and time periods vary from winter to summer, in this study were considered the winter values. Table 1 shows the electrical energy cost during the four periods of a winter working day. It is important to state that in addition to the cost of energy, an additional value is charged for the active power during the peak period. This additional value inflates the cost of the energy during the period of higher demand to incentive consumers to moderate consummations during this period. There exist another cost associated with the electrical energy, the contracted power, which results from the maximum active power absorbed from the power grid during a 15 minutes consecutive interval, with a cost of 0.032 €/kW/day.

Table 1: Electrical energy cost during the four periods of a winter working day.

Period	**Hours**	**Energy cost**	**Additional costs**
Peak (Total 5 hours)	09:30 h – 12:00 h 18:30 h – 21:00 h	0.113678 €/kWh	0.2263 €/kW/day
Half-peak (Total 12 hours)	07:00 h – 09:30 h 12:00 h – 18:30 h 21:00 h – 24:00 h	0.108543 €/kWh	
Normal off-peak (Total 3 hours)	00:00 h – 02:00 h 06:00 h – 07:00 h	0.080717 €/kWh	
Supper off-peak (Total 4 hours)	02:00 h – 06:00 h	0.070637 €/kWh	

Considering the energy consumption profile for the conventional and proposed public DC fast charging station, presented in Figure 4, and the real energy rates for an actual electrical installation presented in Table 1, it is possible to determine the total energy cost during a working day for both scenarios. Figure 5 (a) shows a comparison in terms of total costs with electric energy during a working day between the conventional and the proposed public DC charging station. It is possible to see in the figure that the most significant part becomes from the energy consumed during half-peak periods (12 hours/day). With the proposed topology it is possible to shift the energy consumed during peak to super off-peak periods allowing a significant economy in terms of costs. The total daily energy cost without load shift is calculated in € 411.6 and the daily energy cost with load shift is calculated in € 319.4 resulting in a profit of € 92.2/day. In terms of equipment, it was considered the cost of the substation transformer and auxiliary protection switch boards, the cost of the 10 fast charging posts, the cost of the solar photovoltaic panels with power converters, and the cost with the bidirectional converter, cost of storage batteries and auxiliary power converts that only exists in the proposed topology. Figure 5 (b) shows a comparison in terms of total costs with equipment to implement the conventional and the proposed public DC charging station. As it is possible to see in the figure, the more significant part of the costs without load shift becomes from the fast charging posts. With the load shift strategy, the cost of the charging stations is significantly lower, however the cost with the storage batteries, which is the more significant inflects the total cost of implementation to € 254700 instead of € 185500, related to the first topology. According to these values, it is possible to calculate an additional implementation cost of € 69200 for the proposed topology. However, due to the € 92.2 daily economy in terms of electric energy, the proposed topology can be a long term better solution, because the extra cost of implementation can be recovered in almost two years.



(a) (b)

Figure 5: Comparison between the conventional and the proposed public DC charging station: (a) Total costs with electric energy during a working day; (b) Total costs of equipment required to implement the charging station.

It is important to explain that the cost with the storage batteries is estimated to have a takeover price of 20% of the price of new batteries, and represents 47% of the total equipment cost for the proposed solution. This cost is decreasing consistently along the last years and it is expected that will continue to decrease (McCal, 2011). So, the proposed solution that is very dependent of the storage batteries cost, will certainly be the most advantageous solution in the near future. In addition to economic benefits, the topology presented has many technical advantages for the electric power grid, since it consumes the necessary energy in a more gradual way and avoiding peak periods of consumption. With the evolution of Smart Grids technology, the proposed topology will be even more advantageous since it would allow active participation in the energy markets, allowing to buy energy in the most favorable periods and even to sell energy to the power grid if convenient.

CONCLUSION

In this paper is presented a new concept of a public DC fast charging station for EVs. The main advantages of the proposed topology are the load shift capability and the easy integration of renewable energy sources. The Energy Storage System (ESS) in this proposed charging station can be mainly composed by reused electrochemical batteries from EVs. The system is composed by a set of power converters. One AC-DC bidirectional converter is used to interface the DC link of the charging station with the power grid. The interface with the storage batteries is done by means of bidirectional DC-DC converters, one converter for each battery pack. The charging posts are implemented by means of DC-DC buck-type converters, one for each individual charging point. The interface of renewables can be implemented by means of a simple DC-DC converter. In terms of performance, the proposed topology with the suggested load shift control scheme, allows a significant reduction in the maximum power absorbed from the electrical power grid. In terms of economics, for the case study here presented, considering the current price of batteries and the present electric energy costs, the payback time of the proposed topology is about 2 years.

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