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ORIGINAL ARTICLE

Modular Approach to Ultra-fast Charging Stations

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Abstract

Road transport electrification is essential for meeting the European Union's goals of decarbonization and climate change. In this context, an Ultra-Fast Charging (UFC) system is deemed necessary to facilitate the massive penetration of Electric Vehicles (EVs) on the market; particularly as medium-long distance travels are concerned. Anyway, an ultra-fast charging infrastructure represents the most critical point as regards hardware technology, grid-related issues, and financial sustainability. Thus far, this paper presents an impact analysis of a fast-charging station on the grid in terms of power consumption, obtained by the Monte Carlo simulation. Simulation results show that it is not economical convenient size the assumed ultra-fast charging station for the maximum possible power also considering its high impact on the grid. In view of the results obtained from the impact analysis, the last part of the paper focuses on finding a method to reduce the power installed for the DC/DC stage while keeping the possibility for the electric vehicle to charge at their maximum power. To achieve this goal a modular approach is proposed. Finally, two different modular architectures are presented and compared. In both the solutions, the probability of having EVs charging at limited power is less than 5%.

Keywords Electric vehicles · Charging station · Ultra-fast charging · Modular infrastructure · Transportation electrification

Abbreviations

EV	Electric Vehicle
PEV	Plug-in Electric Vehicle
BEV	Battery Electric Vehicle
UFC	Ultra-Fast Charging
BMS	Battery Management System
SoC	State-of-Charge
Pc	Charging Power
Ebat	Capacity of the Battery
Crate	Charging Rate
Q_C	Battery available capacity
Q_n	Battery rated capacity
FdF	Frequency distribution Function
pdf	Probability density function
b	Weibull shape parameter
a	Weibull scale parameter
μ	Average value
σ	Standard deviation

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1 Introduction

Road transport electrification is inevitable for meeting the European Union (EU) aims of decarbonization and climate change, since this sector is responsible for about 20% of CO2 emissions within the EU [1]. Electric Vehicles (EVs) running only on electricity have zero tailpipe emissions, but there are upstream emissions coming from manufacturing cycle and from electricity generation [2]. Concerning the latter, it is clear that the use of relatively low-polluting energy sources for electricity generation will lead to a stronger well-to-wheel emissions advantage of EVs over similar conventional vehicles running on gasoline or diesel. Instead, in regions that depend heavily on coal for electricity generation, EVs may not demonstrate a strong Well-to-Wheel (WTW) emissions benefit, as shown in [3], where the region with the highest carbon intensity is Germany. For this reason, the introduction of EVs on the market and the installation of Renewable Energy Sources (RESs) are rising hand in hand. The degree of electrification together with the traffic conditions are two other important factors to consider in the WTW analysis [3, 4]. Eventually, from an analysis of independent life cycle assessment (LCA) studies [4–7], it is possible to conclude that a BEV over its lifetime produces 50% less CO2 emissions than a standard EU car today (Fig. 1).

Electric cars are expected to account for 16% of the global car fleet in 2030, rising to 51% in 2040 and to 69% in 2050 [8]. On one hand this electrification process will lead to a significant drop of the average GHG emissions; however, on the other hand, it will require the integration of vehicles into a reliable and affordable as well as easy-of-use infrastructure for the supply of energy [9].

Nowadays, slow charging is the most popular method of charging EVs, in fact is preferred by many car owners when they intend to stay for a long period at the destination such as at home overnight or at the job location during the working day [10, 11]. Slow charging points typically have power ratings that vary from 3 kW (1-phase) up to 22 kW(3-phase) and hence required charging times which last usually between 3 h up to 11 h [12]. Nevertheless, slow charging methods can not satisfy the entire needs of the electric mobility field. Particularly, as medium and long-distance trips are concerned, an Ultra-Fast Charging (UFC) system is necessary for more widespread electric vehicle adoption [13]. In fact, the availability of a fast-charging infrastructure has demonstrated to be a crucial element that strongly and positively influences the driver's behavior in terms of average distance traveled, reduction of range anxiety, and general higher confidence with EVs [14].

Nevertheless, such a charging system has to face a number of serious challenges. First of all, it requires high initial investment costs [15, 16], since its installation involves upgrades in the power infrastructure such as the introduction of new transmission and distribution lines. Although the cost of fast charging equipment is about 10 times higher than that of conventional chargers, its return on investment is, in many cases, faster; since it allows to serve more vehicles a day. Another key factor in the relatively poor presence of UFC systems is its impact on the voltage stability of the distribution network [17–19]. This system can cause, in fact, voltage fluctuations and flicker, which, however, can be almost completely mitigated with the use of both smart

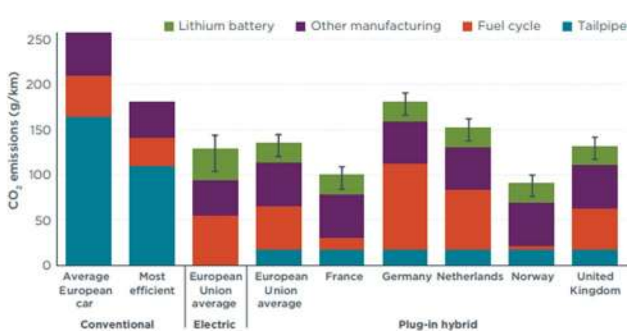

Fig. 1 WTW GHG emissions for different electricity production and degrees of electrification [3]

charging algorithms and on-site distributed energy resources [18]. Moreover, the charging capacity of the different electric vehicles up to now on the market varies in a wide range, making in this way, difficult the choice of the optimal size for such a charging system: if the UFC station is sized for the maximum charging power allowable by the EVs, then it will operate for most of the time at a lower rating leading in this way to poor efficiency values.

Thus far, this paper aims to quantify the effective impact of an ultra-fast charging station on the grid. Factors such as the differences among electric vehicle models, initial SOC, and different arriving times to the charging point are considered in the Monte Carlo simulation. Due to the low load factors, high initial costs, and low flexibility the concept and the advantages of a modular and reconfigurable charging station are introduced. This adaptability could result in a particularly important feature today as innovations and new materials continue to be introduced into EV battery and power-stage components [19, 20]; not to mention the differences that already exist between different typologies and models of EVs. Finally, two modular architectures are proposed and preliminary compared in this paper.

2 State of the Art

In this paragraph, the current state of the art of ultra-fast charging station for EVs is described.

Due to large power requirement, a UFC station needs a connection to the medium voltage MV network [21], indeed in [22] Sun et al. present that a DC fast charger connected to the MV grid can lower about 75% of the losses with respect to a charger of the same power connected to the 480 V grid. The grid medium voltage is then stepped down by an isolating Line Frequency (LF) transformer whose secondary will be converted in DC. The typology of transformer depends on the AC-DC converter chosen [23]. However, in recent years a lot of research is focusing on substituting the line-frequency transformer with a Solid-State Transformer (SST) [24–28]. Such approach will enable the direct connection of the station to the MV line by providing step-down, rectification and isolation functions in a single unit. The adoption of such technology will lead to a lighter, cheaper and more efficient system. In fact, compared with traditional transformer, the SST presents some benefits such as the exploitation of a high-frequency transformer, a better fault current limiting capability, a lower cost and higher flexibility. Despite its advantages, some serious issues, in particular, in terms of reliability and protection devices could potentially limit the applicability of SSTs [26, 27].

Before establishing the AC-DC converter, the first decision to be made in the design of a UFC station is whether to follow a common AC or a common DC bus approach as shown in Fig. 2. Nevertheless, this holds only in case of line frequency transformer, in fact if the SST is chosen as connection to the grid, a common DC bus configuration is the only possible solution, since the mentioned technology covers the functionality of LF transformer and AC/DC conversion.

In an AC bus configuration, the secondary winding of the LF transformer is used to individually supply the charging columns. Therefore, with such an approach all the charging units have their own rectification stages connected to the AC bus. In [29] a EVs fast charging station integrated with an energy storage system is implemented following the AC-bus scheme. The main reason behind the authors' choice is that the AC system is a well-integrated technology for which there are well-developed standards and technologies on the market. However, the DC bus approach is becoming the preferred solution because of its several advantages over the AC bus approach [30, 31]. First of all, a DC bus-based system allows a reduction of the number of components, since a common AC/DC converter is used. With fewer conversion stages an improvement of both the efficiency and the cost of the overall system is possible. For instance, in [32] authors estimate that in DC bus systems the conversion losses can be decreased from about 32% to less than 10% with respect to an AC bus architecture. Moreover, the absence of reactive power allows an easier control, [16, 33]. With a DC bus architecture is also easier to integrate Renewable Energy Sources (RESs) and Energy Storage Systems (ESSs) that can be used to mitigate the negative impact of the UFCS on the distribution MV grid [30]. This fact must not be underestimated, as a matter of fact in [34] authors shown that fast charging stations can increase the peak demand by about 9%, hence causing in addition to the voltage flickers also the drop of the bus voltages bellow the admissible limit (-0.95 pu). The advantages of inserting ESSs and RESs is highlighted in different works. In [35], the authors proposed an energy management system for a fast-charging station (FCS) composed of two fast chargers of 48 kW, a battery energy storage system consisting in a 23.9 kWh Li-ion battery, and a PV system with a peak power of 119kWp. The results of this work show that with the designed configuration the FCS mainly operates in stand-alone mode, and hence almost completely canceling the impact on the grid. On the other hand, according to [26], the major issues of a common DC bus architecture are related to the protection and metering devices.

Since in a UFC station electric vehicles seek considerable level of energy in very short time intervals, the implementation of a bidirectional power flow is counterproductive [36]. In this context, if only unidirectional current flow is requested a three-level three-phase Vienna rectifier represents one of the most suitable candidates to perform the common AC/DC stage [16, 23] in a DC bus configuration. This topology, shown in Fig. 3, with a lower number of active switching devices compared to the other three-level converters, features a highly sinusoidal input current, low voltage stress in the devices, a high-power factor operation and a high reliability in case of malfunctioning, in fact, it is well protected in case of short circuit and it can even operate

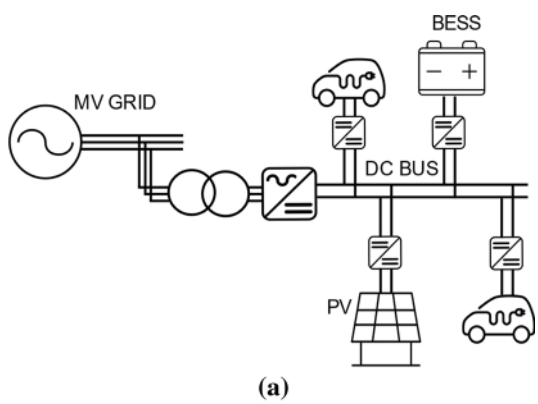

Fig. 2 Charging station architecture: **a** DC bus **b** AC bus

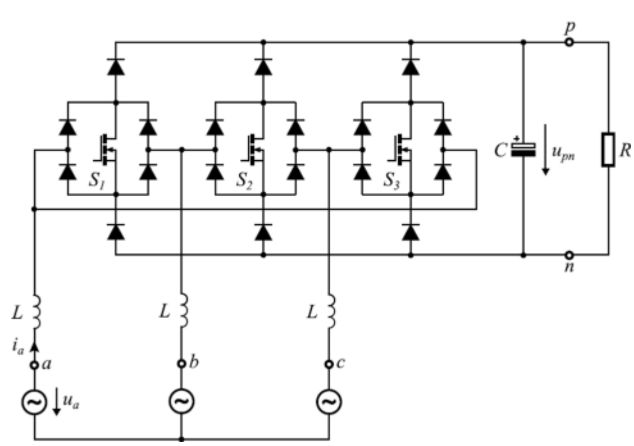

Fig. 3 Vienna rectifier

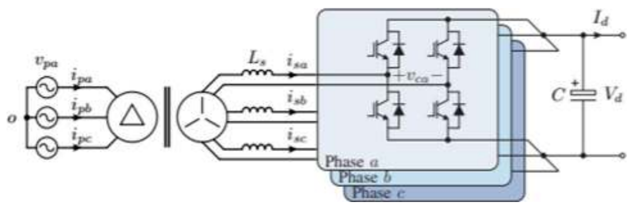

Fig. 4 Power circuit of the HB converter in [38]

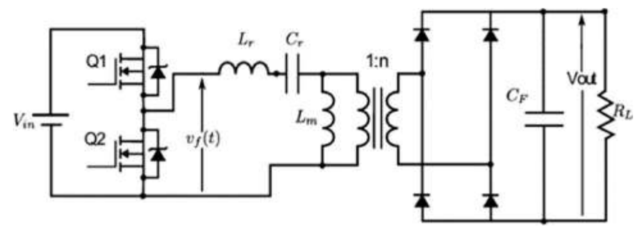

Fig. 6 LLC resonant converter

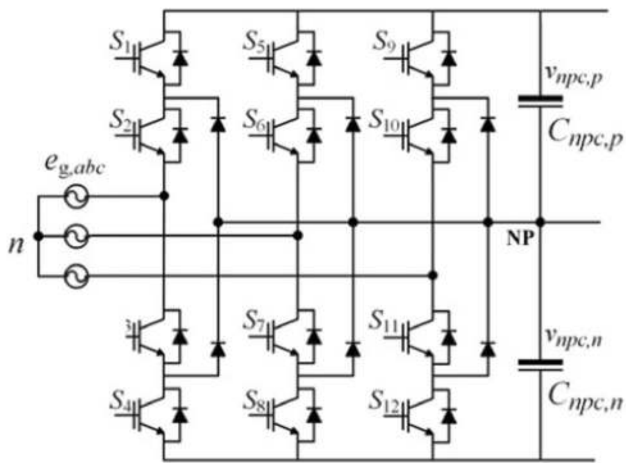

Fig. 5 Three-level three-phase NPC converter

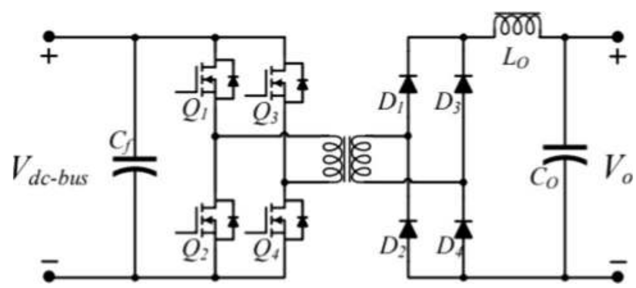

Fig. 7 Power circuit of a PSFB converter

with the loss of one input phase [37]. Its major limitations are the need for dc-link capacitor voltage balancing and the limited reactive power control.

Another rectification stage becoming popular in fast charging station is the multilevel ac/dc converter [38, 39]. In particular the typologies of multilevel converters which seems to be more promising in the field of charging station for EC are the cascade H-bridge (CHB) and the neutral point clamped (NPC). For instance, in [38], Rivera et al. propose a 3-level h-bridge (HB) converter rated as 690 V and 1.2 MW as the grid interface in a dc charging station; its configuration is shown in Fig. 4. The main points in favor of the proposal are the low THD values and the lack of unbalances issues both in the ac and dc sides; moreover, the converter achieves an output three-level waveform without any balancing requirements and without the use of clamping diodes, which instead are necessary in the (NPC) converter proposed as grid interface in [42]. The use of the NPC converter, depicted in Fig. 5, automatically leads to a bipolar DC-bus architecture, which offers as main advantages high power capacity and better current performances, however it produces power imbalances between the positive and negative output bars [41]. In [40] a CHB converter is again proposed as ac/dc stage in a UFC station.

After the AC/DC stage, the DC/DC converter provides an interface to the EV battery. A requirement expressly demanded in IEC 61,851-23 [40] for multiport charging stations is the galvanic insulation between each individual output. The reason for this requirement is the need to constantly monitor the insulation between the DC active parts (positive and negative pole) and the protective conductor or exposed conductive parts of the vehicle (which can be touched) in order to quickly detect a fault and disconnect the power supply. This aim can be achieved by using an isolated DC/DC converter.

Recently an isolated unidirectional DC/DC converter which is gaining ever more attention is the LLC resonant converter, whose scheme is reported in Fig. 6. The LLC converter presents many advantages over other resonant topologies [42, 43], such as: the ability to operate at Zero-Voltage Switching (ZVS) or Zero-Current Switching (ZCS), a wide output voltage regulation, and very high efficiency. Moreover, its output filter consists only of a capacitor and not of an inductor and capacitor (LC) filter [16]. A more comprehensive description of this type of converter is provided in [24] and [44].

In [45] authors design a 50 kW phase-shift full-bridge (PSFB) converter used EV battery interface for fast charging application. This type of isolated dc/dc converter, shown in Fig. 7, is very common in high-power applications, this is due to its most desirable features such as high efficiency at high switching frequency attain through zero voltage switching, its simple design, and easy control method.

A more complete review of the isolated dc/dc converters suitable for fast charging stations can be found in [46].

All the reference papers cited in this section highlight the different studied aspects of fast charging stations. As can be seen, most of the research focuses on the following topics: FCSs connection to the grid, their internal operation and design, their impact on the grid, the importance of an integration with RESs and ESSs, and the different EMSs that can be used. However, few studies focused on the sizing problem of a fast-charging station, as a matter of fact the power rate of the charger in all the reference papers is chosen a priori, without performing any investigation. As the name suggest, a UFCS aim to charge the EVs batteries as fast as possible. Therefore, the first aim of this work is to compute the maximum power absorbed by a UFC station composed of 10 charging ports, considering different aspects such as the different characteristics of today existing electric cars and their stochastic behavior.

3 Impact Analysis on the Distribution System by Monte Carlo Simulation

Ultra-Fast Charging requires a big amount of energy within limited intervals of time resulting in a very high-power density. This feature may pose undesirable issues on the national electric grid such as feeders and transformers overloading problems [28, 47], voltage drops [28, 48], and harmonic resonance risk [48]. Therefore, there is a need to investigate and model the impact on the grid of such a charging system. In this paragraph, the theoretical peak demand for electricity of a UFC station is carried out. More precisely, the power absorbed by the entire station is computed without going into the power delivered by each single charging pole.

3.1 Considered Key Factors

In the case of UFC station, the infrastructure is shared among different types of vehicles, which, having different charging profiles, require diverse charging strategies. More and more often it is possible to hear about very high power charger, able to provide 350 kW; nevertheless, as shown Fig. 8, only a few EVs nowadays allow a charging power higher than 100 kW; in fact, the charging time does not depend only on the output power of the charger but it is determined by the vehicle charging capability, which in turn depends on multiple factors.

The characteristics of the battery which influence the charging process, considered in this analysis, are listed below.

1)Capacity of the battery (E_{bat}): The larger is the battery capacity of the vehicle the higher can be the allowed charging power [50]; in fact, according to (1), for a given value of injected power as the capacity of the battery becomes larger, the C_{rate} is reduced:

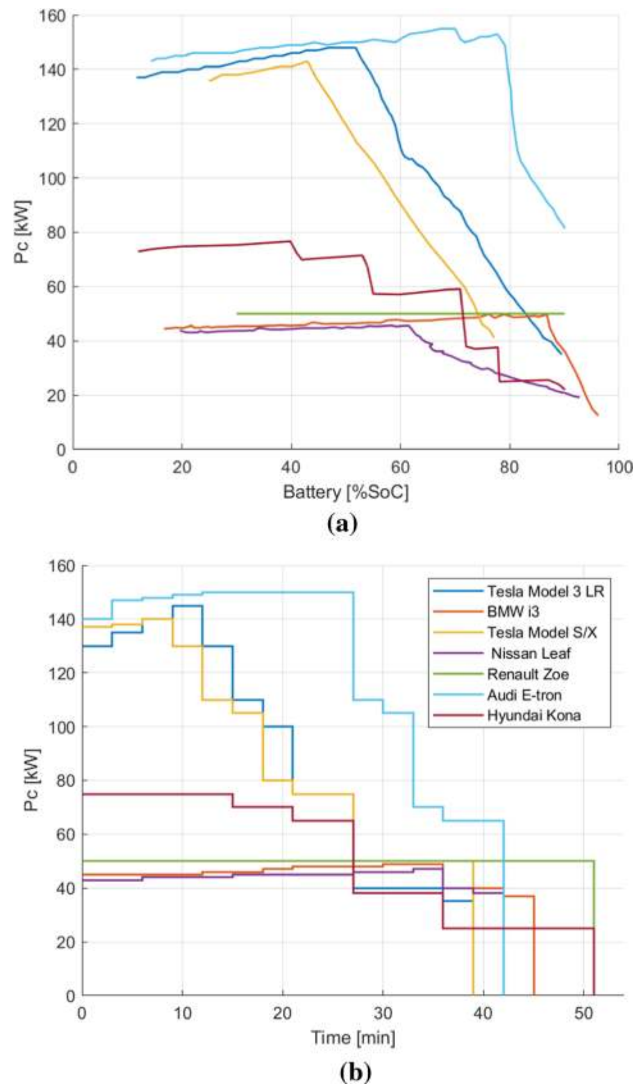

Fig. 8 Charging profiles of different EVs **a** as a function of %SoC [49], **b** as a function of time

$$C_{rate} = \frac{P_c}{E_{bat}} \tag{1}$$

where Pc indicates the charging power and Ebat the battery capacity. The C_{rate} is the measure of the speed at which the battery is charged/discharged. High c-rates result in high aging rates. In fact, charging Li-ion batteries at a rate higher than 1C causes uneven heat generation inside the cell, mechanical pulverization of the electrode materials, and the occurrence of lithium plating reaction [50–53]. Therefore, the manufacturers have to deal with all these restrictions and set their limits through the Battery Management System (BMS), which will drive the charging process according to the proper charging profile and the allowed maximum charging rate of that specific vehicle [54].

2) State-of-Charge (SoC): The SoC of a cell, expressed in (2), is defined as the percentage of currently available capacity (Q_c) to its rated capacity (Q_n) [55], and its value ranges between 0% up to 100%.

$$\%SoC = \frac{Q_c}{Q_n} \cdot 100 \tag{2}$$

In general, the charging speed is strongly influenced by this factor. In fact, as the battery approaches a SoC around 60–70%; the charging rate stars to drop quickly [56, 57]. Therefore, fast charging above 70–80% of the battery is not very useful.

3) Another external factor that can have a significant influence on charge speed is the temperature of the battery [58–60]. A battery works optimally if the temperature is not too high and not too low and in practice, this is usually between 15 and 35 ° [61]. Nevertheless, such a factor is not considered in this study.

To consider in the analysis the above-mentioned features, which influence the charging process, a fleet of seven different electric vehicles, chosen among the top-selling models in 2018 and 2019, has been assumed in this study. The main characteristics of the chosen BEV models are reported in Table 1.

Figure 8a shows the charging profiles of the chosen models. Such trends are computed in optimal conditions, which means at ambient temperature and with new batteries. The charging profile $Pc(\%SoC)$ of each vehicle has been discretized and then plot as a function of time (Δt), according to the (3). Finally, Fig. 8b reports the obtained discrete trends.

$$\Delta t = \frac{Pc \cdot \Delta SoC(\%)}{E_{bat}} \tag{3}$$

At the end of each charging process, an interval lasting 3 min in which the charging power is nil has been introduced. This interval aims to reproduce and incorporate the time needed: to pay the recharge, to disconnect the full charged vehicle, to connect, validate, and to start charging the new connected one. In almost all the trends, the charging profile stops when the vehicle battery reaches 90% of SoC.

The assumed station is composed of ten charging poles each one able to provide 175 kW, for an overall maximum power of 1.75 MW. The theoretical maximum peak is then found assuming that ten vehicles, casually chosen among the seven models previously introduced, simultaneously occupy the ten poles. Once the vehicle is selected, its instantaneous charging power is randomly picked among the values in the corresponding charging profiles. This last passage aims to replicate the different arrival times to the station.

Table 1 Features chosen BEVs

BEV model	Declared autonomy (km)	Battery capacity (kWh)	Battery technology
Tesla Model 3 LR	530	75	Li-ion
BMW i3	260	42.2	Li-ion
Tesla Model S LR	417	75	Li-ion
Nissan Leaf	305	40	Li-ion
Renault Zoe	395	52	Li-ion
Audi E-tron	400	95	Li-ion
Hyundai Kona	482	64	Li-ion

3.2 Analysis and Discussion of Results

In this way, 100.000 different scenarios are simulated. The number of bins is set according Sturge's rule in (4) and rounds up to 18.

$$k = 1 + 3.322\log_{10} N = 17,67 \tag{4}$$

where k represents the number of bins and N is the number of observations.

Then, it is possible to define the relative frequency of each event as the ratio between the number of occurrences of that value and all the results of possible scenarios. The Frequency density Function (FdF) of the overall power simultaneously absorbed by 10 e-vehicles is reported in Fig. 9. The FdF is fitted with a normal distribution and with a Weibull one, whose expression are reported respectively in (5) and (6).

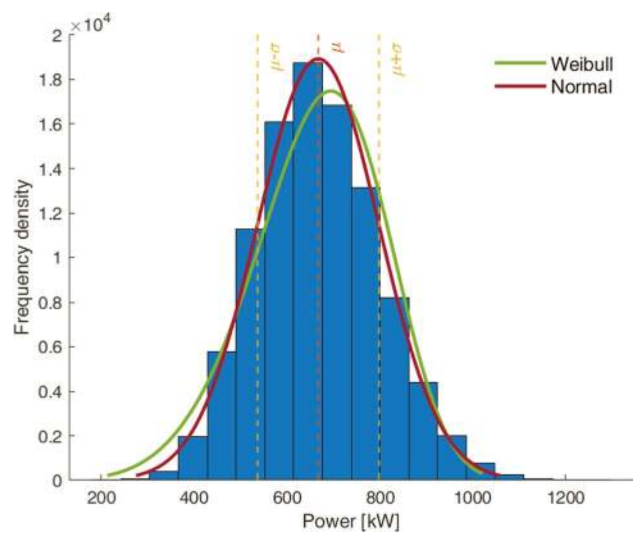

Fig. 9 Charging station power probability density function

The Weibull probability density distribution is expressed as:

$$f(x|a,b) = \frac{b}{a}\left(\frac{x}{a}\right)^{b-1} e^{-(x/a)^b} \quad (5)$$

where b is the shape parameter and a scale parameter. Particularly, in this study, these two parameters, which define the Weibull distribution, result respectively about 720 and 5.43.

Instead the expression of the normal probability density function (pdf) is:

$$f(x|\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(x-\mu)^2}{2\sigma^2}} \quad (6)$$

where μ is the mean and σ the standard deviation. The mean of such distribution is computed thorough (7) and results about 667 kW, as a consequence of the central limit theorem. Therefore, the results are strongly influenced by the models chosen to form the fleet, in other words this is a consequence of the influence of the battery capacity and SoC.

$$\mu = \frac{\sum_{i=0}^{N} x_i}{N} \quad (7)$$

where x_i is the value of the power absorbed in the i-th instant and N is the number of different instants/scenarios considered, in this case 100,000.

The standard deviation is instead computed through (8) and results about 130 kW.

$$\sigma = \sqrt{\frac{\sum_{i=0}^{N}(x_i - \mu)^2}{N}} \quad (8)$$

From such results, it is possible to conclude that by considering a UFC station able to provide a maximum power of 1 MW is possible to satisfy more than 97.6% of probable scenarios. It is important make clear that the found peak demand does not represent any particular moment of the day, but it is a theoretical peak used to give a first size of an UFC station; moreover, the power conversion efficiency has not been considered.

4 Modular and Flexible Design Proposal

Given the results reported in the previous section, it may be concluded that to size the considered charging station, composed of 10 charging ports, for an overall power higher than 1 MW it is not economical convenient, also considering its high impact on the grid. Therefore, now the attention moves to find a method to reduce the total power installed for the DC/DC converters while keeping the possibility for the EVs to charge at maximum power.

To achieve this objective a modular design is here proposed. According to such an approach, the DC/DC stage is composed of identical modules working in parallel configurations. These modules as shown in Fig. 15a are input parallel connected to a common DC bus bar, instead their outputs can be paralleled in different ways thanks to the presence of smart power switching devices. The different configurations of modules can be used to feed individual EV batteries, thus leading to the capability of simultaneously charging several electric vehicles at different power levels. Given the choice of the common DC bus, as previously mentioned, different types of RESs and ESSs can be easily integrated into the station design; however, in this work only the design of the chargers is addressed.

This modular and reconfigurable approach offers many advantages:

1. It simplifies the maintenance and replacement procedure [62]. The modules can be added and removed without compromising the functioning of the overall system.

2. It increases the flexibility for future expansions and future power requirements [63, 64]. In fact, in the next years, more vehicles are expected to become capable of charging at high speeds [65] and this approach gives the possibility to easily scale up the power installed any wanted time with minimized processes [66]. This will allow the UFC stations of today to be compatible with tomorrow's requirements, minimizing and spreading the total cost of ownership and the initial investment over the years.

3. It allows much better use of the installed capacity [55]. As shown in Fig. 10, for a given value of installed power, the modular approach allows better management, enabling in fact to fully satisfy a higher number of simultaneous charging processes requiring different power values.

4. It enhances high efficiencies at low load. The vehicle characteristics and consequently their power charging requirements may differ considerably among the models and the different levels of SoC, for this reason, the converters of a conventional UFC station are sized for the maximum power, but they operate most of the time at a lower rating resulting in low light-load efficiencies. A modular architecture aims to improve this feature since it enables a more split use of the installed power.

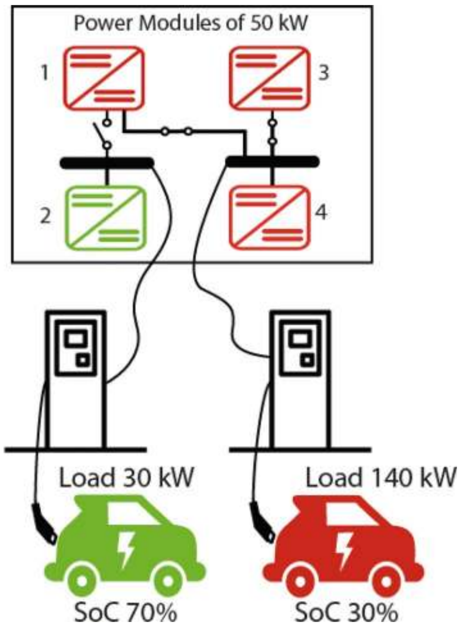

Fig. 10 Example of modular charging station

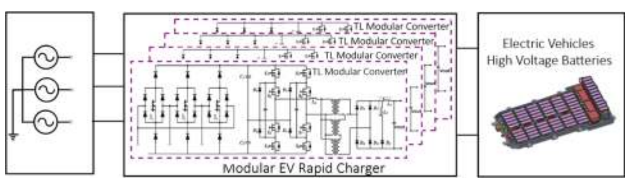

Fig. 11 Block-diagram of the converter proposed in [67]

5 The design of the cooling system is simplified in the case of modular architecture and the overall system reliability increases.

In literature different types of modular charger and station have been analyzed [67, 68]. In [67], indeed, a modular converter topology for EV fast charging, shown in Fig. 11, has been proposed. The charger proposed is a 50 kW rapid charger which consists of four 12.5 kW modules paralleled connected both at the input and output. Based on the power required by the EV battery a certain number of converters is activated for the charging process. The major strength of this design is the optimization of the overall system efficiency and power density. However, in this case all the modules include the rectification stage resulting in higher costs with respect to the modularization of the dc/dc part only. Moreover, in this type of design, the split of the power is allowed only for the corresponding charging

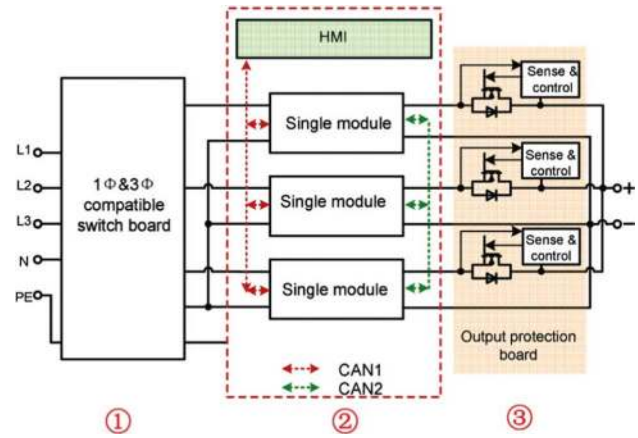

Fig. 12 Modular onboard charger [68]

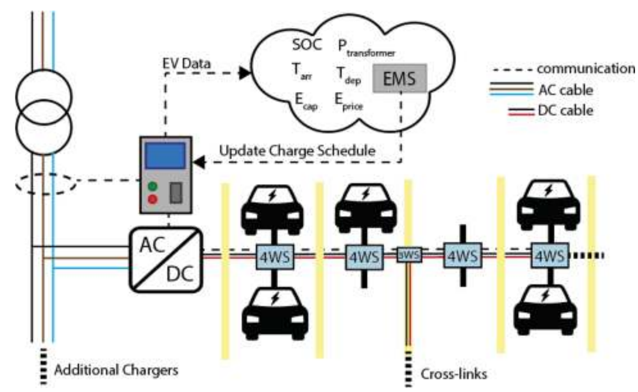

Fig. 13 reconfigurable DC charging network in [69]

port and the modules cannot be shared with the other ports within the charging station.

In Fig. 12 the modular onboard charger presented in [68] is depicted. The logic behind and the design is very similar to the converter proposed in [67], with the difference that this one is installed onboard. Precisely, the onboard charger is composed by three 3.3 kW modules paralleled connected. Hence the output power of the charger can be enlarged to achieve higher charging rate by paralleling more modules, up to a maximum power of about 10 kW. As the approach described in [67], also this system aims to increase the efficiency at light load operation and to improve charger redundancy.

A reconfigurable, but not modular, charging network is then presented in [69]. As shown in Fig. 13, this charging network bases its operation on controllable switches, similarly to the architectures that will be proposed in this paper. However, the reconfiguration of the network in [69] aims only to achieve the best charging pattern of the connected EVs to minimize the charging cost. In fact, the EVs parked at the station are all connected to a single charger, but they are filled one at a time, following the optimized charging schedule dictated by the energy management system (EMS).

Finally, in [70] a fast-charging system based on a modular reconfigurable architecture is presented. In Fig. 14, the block diagram of the switching scheme proposed for the charging station is fully depicted. Each of the 15 kW modules is composed of a three-phase voltage source rectifier (VSR) and an isolated full-bridge dc/dc converter.

The modules are input paralleled connected, instead the outputs can be parallel, or series connected to achieve higher charging current in the first case and to be compatible with EVs with higher battery voltages such as electric buses and trucks in the second configuration case. Particularly, the automatic power distribution unit shown in Fig. 14 allows all these configurations. Nevertheless, this unit allows only the output series/paralleled connection of maximum 2 modules, leading in this way to a maximum charging power of 30 kW.

5.1 Proposed Architectures

The paper proposes and analyzes two basic architectures. In both cases, the UFC station is composed of 10 charging ports and 20 50 kW modules. The modules are imagined to be in a common shelter with assumed disposal of 10 per row. In both the architectures the modules located in the lower row are fixedly connected to the corresponding output DC bus bar which in turn is connected to a single charging port. Therefore, these modules are dedicated only to the charging of the vehicle connected to that corresponding charging column. Instead, the modules positioned in the upper line are shared according to the possibilities allowed by the commutators.

The first architecture analyzed (1ST), whose part of the main scheme is reported in Fig. 15a, presents 20 commutators (S1–S20), two for each module placed in the upper row. Figure 15b, instead, highlights the out modules connections and the switched disposition; for the sake of simplicity, through a single-line diagram.

The decision flowchart of this first proposed configuration is fully depicted in Fig. 16, by taking as example an electric

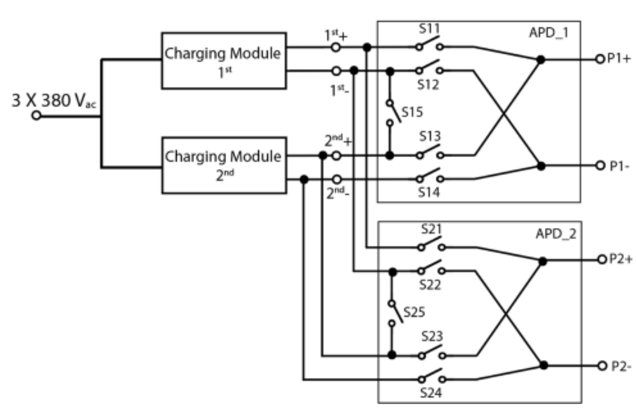

Fig. 14 Switching scheme block diagram used in [70]

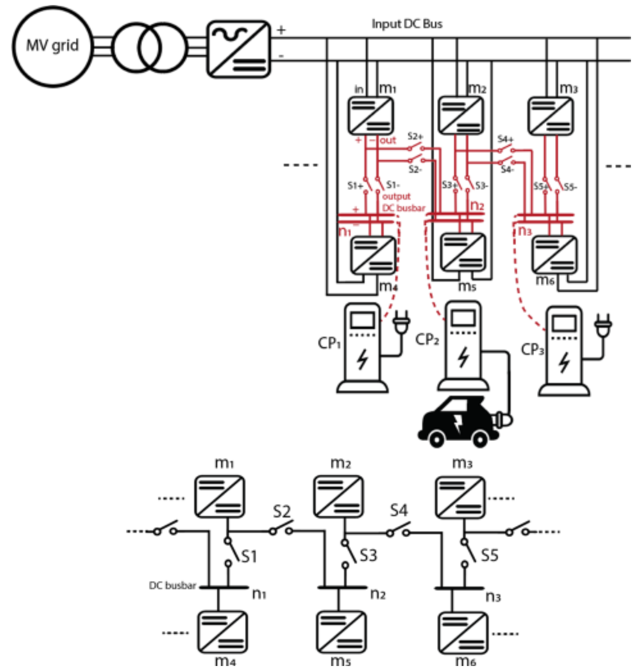

Fig. 15 First proposed modular architecture block diagram: **a** complete station and **b** modules outputs connection

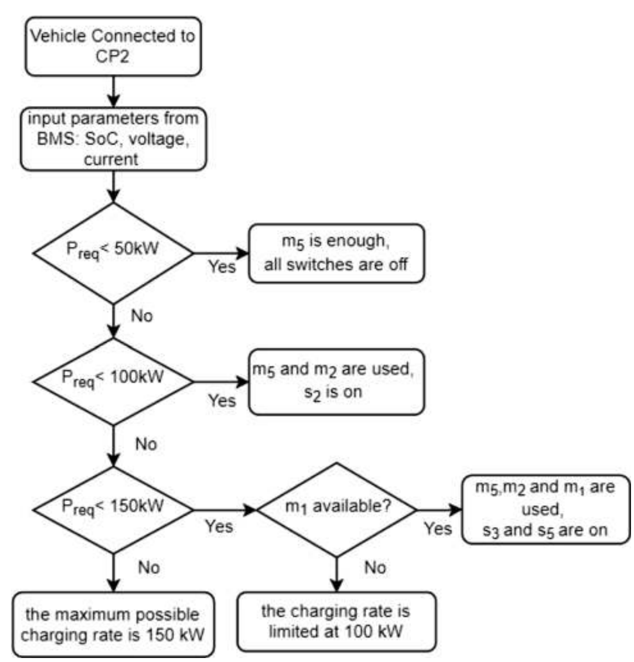

Fig. 16 Decisional flowchart first architecture

vehicle connected at the charging port 2 as represented in Fig. 15a.

From Fig. 16 It is possible to conclude that, in this first configuration, the modules in the upper line can be shared until reaching a maximum power of 150 kW for a given charging port. If one upper module is connected to the adjacent port, it means that the vehicle connected to the corresponding column is charging with a speed of maximum of 50 kW, because for the upper module the vehicle connected to the corresponding charging port takes precedence over the other vehicles connected to the adjacent ports. Therefore, a maximum power of 100 kW is always guaranteed to the vehicles.

The second architecture (2ND) is composed of 20 modules distributed on 10 columns as well. The connection to the electrical grid, which means the input connection to the modules is the same as Fig. 15a. Instead, in Fig. 17 is represented the connection of the output of the DC/DC modules and hence the configuration of the power switches. As Fig. 15b for the first case, only 6 modules over 20 and 3 charging ports over 10 are illustrated to make the representation clearer. If in the first proposed architecture, the up module can be shared only with the next charging port in terms of the order; instead, in the second architecture (2ND), the up module can be used by both the adjacent charging columns.

Therefore, the decisional flowchart for this configuration, shown in Fig. 18, will have more steps. By taking as example always the connection to the charging port 2 (the dc busbar n_2), the additional step consists in checking the availability of both the up adjacent modules in case the vehicle requires a charging power higher than 100 kW. Moreover, the presence of an extra switch for each charging point, and hence 10 extra switches with respect to the first architecture, for a total of 30 in the UFC station considered, allows the connected vehicles to charge a possible maximum power of 200 kW.

The two architectures are then compared, and the outcomes are reported in Fig. 19.

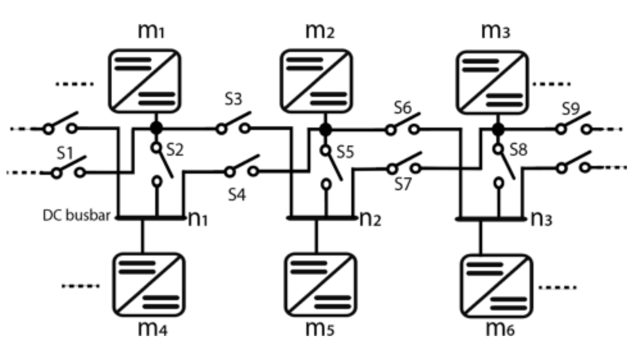

Fig. 17 Second proposed architecture modules output connection block diagram

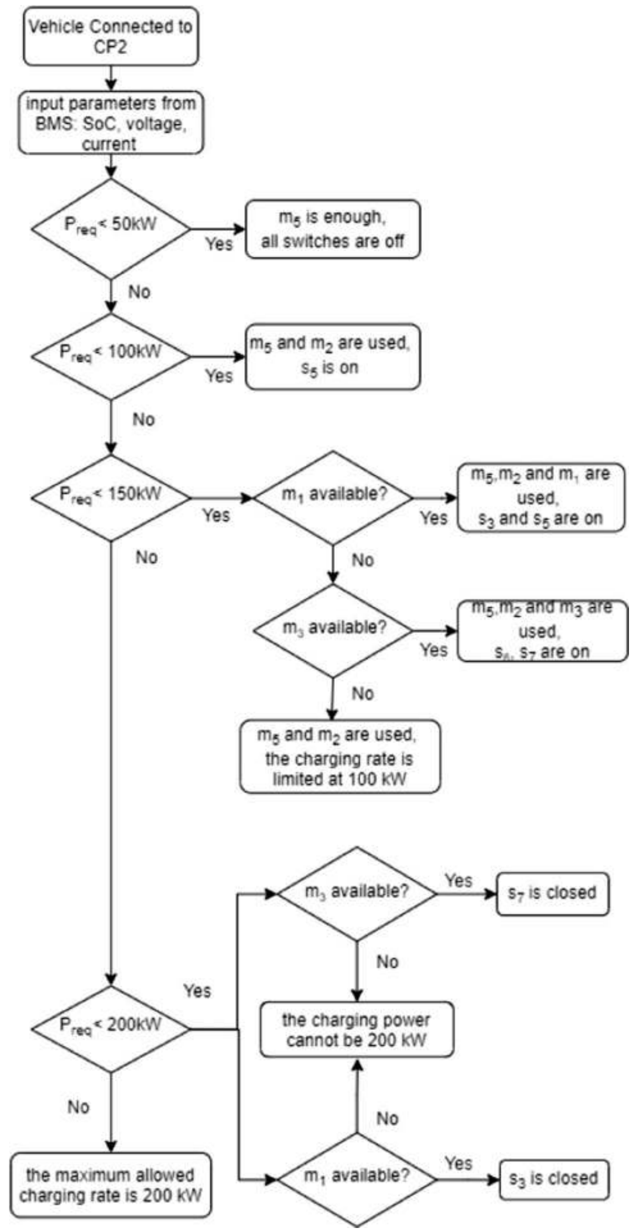

Fig. 18 Decisional flowchart second architecture

The first proposed architecture has only 20 commutators, but it allows a fewer number of configurations resulting in this way in lower costs but also a higher probability for the BEVs to be charged at limited power compared to the allowed one. On the other hand, by increasing the number of commutators, which is increased to 30 in the second proposed architecture, more configurations can be covered, so that the probability of charging EVs with limited power decreases from the 4.1% of the first architecture to 2.1%. The probability is only for those EVs that have charging profiles that allow power values greater than 50 kW; in fact, the lower module is not shared and hence a charging power

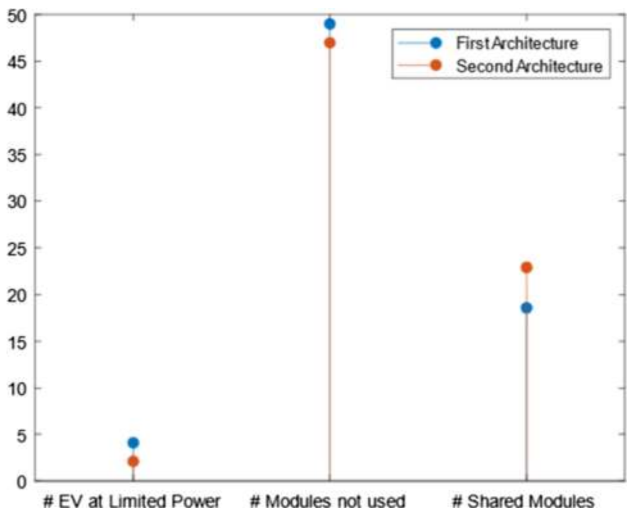

Fig. 19 Comparison proposed modular architectures

of 50 kW is always guaranteed. It can also be concluded from Fig. 19 that in both architectures the percentage of EVs charging at limited power is less than 5%. In the second architecture, the number of shared modules increases as a result of the higher number of possible configurations, so the probability of having unused modules decreases from 49 to 47%.

6 Conclusions

This paper focuses on the design of an ultra-fast charging station for electric vehicles. A probabilistic method for estimating the total absorbed power of the station is presented. The power requirement is calculated taking into account factors such as the simultaneity in the connection and the different charging profiles, and hence characteristics, of the BEVs currently on the market. The result underlines that by dimensioning the overall station with a capacity of about two-thirds of the maximum power, more than 97% of the possible scenarios can still be covered, thus reducing the impact on the network and the necessary initial investment.

A reduction in the overall power of the UFC station automatically leads to a reduction in the power installed for the DC/DC converters. Therefore, in the second part of this paper, a new modular approach, for reducing the installed power for the chargers, while maintaining the possibility of charging all the electric vehicle models at the maximum speed allowed by their charging curve, is investigated. In the proposed modular approach, the DC/DC stage of the UFC station, containing 10 charging points, consists of 20 identical 50 kW modules that can be shared between adjacent charging ports depending on the possibilities allowed by the power switches configuration. Two different switches configurations have been proposed. From the results obtained by the comparison of the two, it can be concluded that the second architecture, with more switches, has a better performance in terms of power-sharing; in fact, only 2.1% of the possibility for an EV to charge with limited power. However, both the proposals allow a greater flexibility in charging vehicles of different sizes, and they also increase the converter's utilization rate and thus the efficiency of the entire charging system.

For the characteristics of the electric cars currently on the market it has been demonstrated that, in both the cases, the probability of charging EVs with limited power is less than 0.05. However, in the future, the maximum charging power allowed by the EVs is likely to increase; for this reason, the next steps of this research will focus mainly on finding other suitable architectures and on the comparison of the results. Finally, since in this work the size of the modules (50 kW) has been selected without a proper investigation, then in future steps will also focus on finding the optimal size of the modules which composes the station will be address.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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