Overview of Integration of Power Electronic Topologies and Advanced Control Techniques of Ultra-Fast EV Charging Stations in Standalone Microgrids

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Overview of Integration of Power Electronic Topologies and Advanced Control Techniques of Ultra-Fast EV Charging Stations in Standalone Microgrids

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Abstract: For longer journeys, when drivers of electric vehicles need a charge on the road, the best solution is off-board ultra-fast chargers, which offer a short charging time for electric vehicle batteries. Consequently, the ultra-fast charging of batteries is a major issue in electric mobility development globally. Current research in the area of power electronics for electric vehicle charging applications is focused on new high-power chargers. These chargers will significantly increase the charging power of electric vehicles, which will reduce the charging time. Furthermore, electric vehicles can be deployed to achieve improved efficiency and high-quality power if vehicle to microgrid (V2µG) is applied. In this paper, standards for ultra-fast charging stations and types of fast charging methods are reviewed. Various power electronic topologies, the modular design approach used in ultra-fast charging, and integration of the latter into standalone microgrids are also discussed in this paper. Finally, advanced control techniques for ultra-fast chargers are addressed.

Keywords: ultra-fast charger; DC-DC converter; rectifier; electric vehicles; off-board charger; modular design; standalone microgrid; advanced control

1. Introduction

The bid to reduce emissions of greenhouse gases requires the electrification of mobility. To meet these expectations, policy and decision makers, the scientific community and automotive manufacturers have devoted increased attention and action related to electric vehicles. Technological progress continues to develop, with the arrival of new devices for power electronics and energy storage materials [1]. These aspects, which allow the transition to the electric vehicle, make it possible for moving in a sustainable way. However, slow battery charging is a major challenge for the development of electric mobility. To overcome these issues, several industries operating in the area of power electronics have moved to off-board ultra-fast chargers [2].

Today, AC slow charging is the most widely used and accessible charging method, as AC power is delivered directly from the grid [3]. This charging infrastructure is inside the vehicle (usually named on-board chargers). Consequently, the power of the battery charger is usually restricted because the volume and weight of the power converter is limited, imposing a slow charging time. AC slow chargers have powers ranging from 3.6 kW to 22 kW, which can generate a charging time ranging from 3 to 11 h [4]. To resolve this problem, DC ultra-fast charging is employed. The volume and weight of the power converter are outside the vehicle (off-board charger), which allows the power of the charger to be increased, thus reducing the charging time. The first DC chargers started at around 50–60 kW, although the new generations of DC fast chargers can provide up to 350 kW [5]. The on-board and off-board charging technologies are presented in Figure 1.
2. International Standards for Ultra-Fast Charging Stations

The number of fast chargers has expanded worldwide. This has led to standards being established for charging systems. Nowadays, there are four ultra-fast charging standards dominant in the world, each using its own connector: CHAdeMO, CCS, Tesla and GB/T. These standards are included in IEC 62196-3, IEEE 2030.1.1, GB/T 20234.3 and SAE J1772.

Table 1 summarizes the important standards for ultra-fast charging stations [12–14]. One of the most widely used techniques for ultra-fast charging is the CHAdeMO protocol. This Japanese standard enables ultra-fast charging with power from 62.5 kW to 400 kW [15]. CCS is an ultra-fast charging protocol for electric vehicles supported by a German association (CharIN e.V); it uses the Combo 1 and Combo 2 connectors, accepting up to 350 kW [16]. Tesla has its own ultra-fast charging protocol available only through the Tesla Supercharger and electric vehicles, with a charging power reaching up to 250 kW [17]. Finally, GB/T is a protocol that is specified only for the Chinese market. For this reason, the new standard, with the working title of ChaoJi, is the result of a partnership with China for compatibility with the GB/T standard, aiming at 900 kW of power. Moreover, there is a partnership between ChaoJi and CCS to make ChaoJi compatible with the CCS standard [18]. CharIN recently developed the Megawatt Charging System (MCS) norm for electric trucks and electric buses. This connector accepts up to 4.5 MW [12].
Another important issue that distinguishes ultra-fast chargers is the power factor. Indeed, a good ultra-fast charger requires a unity power factor ($PF = 1$) [19]. PF is defined as follows [20]:

$$PF = \frac{DPF}{\sqrt{1 + THD_i^2}}$$  \hspace{1cm} (1)

where $THD_i$ is the total harmonic current distortion and $DPF$ is the distortion power factor. Thus, to have a unity power factor, it is necessary that the three-phase current and the three-phase voltage are in phase ($DPF = 1$). On the other hand, the $THD_i$ must be as low as possible ($THD_i \Rightarrow 0\%$). According to the IEEE-519 standard, $THD_i$ must not exceed 5% for a normal situation, with no risk of malfunctions [21].

As can be seen in Table 2, charging stations using the connectors and standards described above are offered by many manufacturers. The technical specifications are obtained from the datasheets of these manufacturers. It is seen that CCS combo 2 and CHAdeMO are the standards most used in the electric vehicle DC fast-charging system market. The power factor values of these chargers vary from 0.97 to 0.99, with a $THD_i$ that does not exceed 5%. In addition, these high-efficiency ultra-fast chargers have a DC output voltage that varies from 150 V to 1000 V. This makes these ultra-fast chargers compatible with most electric vehicles in the industry and also with future electric vehicles based on 800 V battery system, in order to profit from the full power of the ultra-fast charger with a reasonable current (up to 500 A) [22].

### Table 1. Standards for ultra-fast charging systems.

<table>
<thead>
<tr>
<th>Standard</th>
<th>CHAdeMO</th>
<th>CCS Combo 1</th>
<th>CCS Combo 2</th>
<th>Tesla</th>
<th>GB/T</th>
<th>Chaoji</th>
<th>MCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compliant standards</td>
<td>IEEE 2030.1.1</td>
<td>SAE J1772</td>
<td>IEC 62916-3</td>
<td>No associated items</td>
<td>IEC 62916-3</td>
<td>CHAdeMO and GB/T</td>
<td>No associated items</td>
</tr>
<tr>
<td>Region</td>
<td>North America</td>
<td>Japan</td>
<td>Europe</td>
<td>North America</td>
<td>China</td>
<td>Universal</td>
<td>-</td>
</tr>
<tr>
<td>Connector inlet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max voltage (V)</td>
<td>1000</td>
<td>600</td>
<td>900</td>
<td>500</td>
<td>750</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>Max current (A)</td>
<td>400</td>
<td>400</td>
<td>400</td>
<td>631</td>
<td>250</td>
<td>600</td>
<td>3000</td>
</tr>
<tr>
<td>Max power (kW)</td>
<td>400</td>
<td>200</td>
<td>350</td>
<td>250</td>
<td>185</td>
<td>900</td>
<td>45,000</td>
</tr>
</tbody>
</table>

### Table 2. Electrical specifications of ultra-fast chargers from certain manufacturers.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Manufacturer 1</th>
<th>Manufacturer 2</th>
<th>Manufacturer 3</th>
<th>Manufacturer 4</th>
<th>Manufacturer 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country</td>
<td>Sweden–Switzerland</td>
<td>Portugal</td>
<td>Amsterdam</td>
<td>China</td>
<td>Australia</td>
</tr>
<tr>
<td>Charging protocols</td>
<td>CCS-1 and CHAdeMO</td>
<td>CCS-2 and CHAdeMO</td>
<td>CCS-2 and CHAdeMO</td>
<td>CCS-2</td>
<td>CCS-2 and CHAdeMO</td>
</tr>
<tr>
<td>AC input voltage (V)</td>
<td>480–600 (60 Hz)</td>
<td>400 (50 Hz)</td>
<td>400 (50 Hz)</td>
<td>400 (50–60 Hz)</td>
<td>480 (50 Hz)</td>
</tr>
<tr>
<td>Max DC output current (A)</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>DC output voltage (V)</td>
<td>150–920</td>
<td>Up to 920</td>
<td>150–920</td>
<td>200–1000</td>
<td>Up to 920</td>
</tr>
</tbody>
</table>
3. Types of Fast Charging Methods

Charging is the process of providing a battery with DC current from an outside energy source, including a chemical reaction that stores the electrical energy in the form of chemical energy. To enhance the results of this charging both in time and efficiency, different charging methods and processes are applied.

One of the most common fast-charging methods is the constant current–constant voltage (CC-CV) charging. As shown in Figure 2a, a constant current ($I_{Bref}$) is provided to the electric vehicle battery until the maximum acceptable voltage ($V_{Bref}$) is reached. Then, this voltage is regulated to stay constant until the current achieves a cut-off current ($I_{CO}$) [23]. The charging time of the battery can be minimized by increasing the current used during the constant current phase. However, high currents can reduce the lifetime of the battery or create damage on a permanent basis. In fact, the use of a higher current leads to higher losses because of the internal resistance of the battery. These losses are mainly manifested in the form of an increase in temperature in the battery. Consequently, fast charging necessitates an appropriate thermal management, keeping the temperature of the battery in its safe operating zone [24].

Another popular fast-charging method is multi-stage constant current (MSCC) charging, as shown in Figure 2b. The CV stage of the CC-CV method is substituted by a sequence of CC phases with monotonic falling charging currents ($I_{Bref1} > I_{Bref2} > \ldots > I_{CO}$). Each time the battery voltage reaches $V_{Bref}$, the charging current is decreased to the next level. This decrease of current will continue until the battery terminal voltage reaches the maximum acceptable voltage ($V_{Bref}$) under the condition of minimum current ($I_{CO}$) [25]. The charging time of this type of method is a little slower than that of the CC-CV process, with the same initial charging current [26].

Recently, a new ultra-fast charging method was developed, called the KVI Non-Linear Voltammetry solution. This process charges the battery in six minutes while maintaining low temperatures ($<50 \, ^\circ C$) and ensuring a long lifetime of the battery [27].

For controlling the voltage and current profiles of the charger output during the charging process, the electric vehicle must be equipped with a Battery Management System.
(BMS). As presented in Figure 3, this system monitors the voltage of each cell and the temperature, and it gives current and voltage references to the electric vehicle ultra-fast charger controller [28].

![Ultra-fast charging system diagram](image)

**Figure 3.** Ultra-fast charging system.

### 4. Different Power Electronic Topologies of Ultra-Fast Charger

To design a universal ultra-fast charger (adapted to different grid voltages and different battery voltages), two stages are required. As shown in Figure 4, the first stage ensures the AC-DC conversion and guarantees a unity power factor. The second stage provides DC-DC conversion and adapts the voltage of the ultra-fast charger to the voltage of the battery. This voltage varies according to the state of charge of the battery. If galvanic isolation is ensured by the MV/LV transformer, a non-isolated DC-DC converter can be employed [9].

![Structural scheme diagram](image)

**Figure 4.** Structural scheme of the ultra-fast charging systems: (a) ultra-fast charging station with a non-isolated DC/DC converter; (b) ultra-fast charging station with an isolated DC/DC converter.
4.1. AC-DC Power Converters

At the AC-DC stage, the three-phase two-level rectifier, NPC converter, and Vienna rectifier are widely used for off-board ultra-fast charging [29]. They are well-developed converters, the characteristics of which are suitable for the electric vehicle charging industry.

As shown in Figure 5a, the three-phase two-level rectifier (3P-2L) consists of six controlled switches. This power converter generates low total harmonic current distortion, provides bidirectional power flow, and achieves a power factor close to unity, with good efficiency and easy control [11]. However, a bulky filter inductor is required in this rectifier compared to the other three-level topologies to regulate THD, to low values [30].

![Figure 5](image-url) DC-AC converter topologies for electric vehicle ultra-fast charging application: (a) three-phase two-level rectifier; (b) NPC converter; (c) Vienna rectifier.

Figure 5b shows the three-phase three-level neutral point clamped (NPC) converter, which has 12 controlled switches and six parallel diodes and offers bidirectional power flow. The NPC topology has a lower total harmonic distortion, which can further reduce the filter inductor [31]. Moreover, this topology offers a bipolar DC bus, enabling two DC-DC converters cascaded to be connected in series-series or series-parallel configuration [32,33], which can increase the output power of the charging systems. However, this topology requires a higher number of power semiconductors, resulting in a higher cost. Another drawback of the NPC is the complexity of the control system [30].

Since ultra-fast chargers are designed for occasional charging with an electric vehicle plugged in only during the period of the charge, bidirectional energy flow is considered unnecessary. Hence, the Vienna rectifier is the best solution. This three-level converter illustrated in Figure 5c offers a power factor close to unity, lower total harmonic current distortion, high-power density, and good economics, thanks to the reduced number of controlled switches [34].

Table 3 shows a comparison of the previously discussed DC-AC converter topologies using the most popular simulation environments for power electronics (PSIM, PLECS/SpeedFit, and MATLAB/Simulink). According to this comparison, the Vienna rectifier is the best AC-DC converter due to its high quality of output voltages and input currents, and best efficiency with low cost. However, the emergence of photovoltaic systems and storage batteries at charging stations requires bidirectional rectifiers [35]. Therefore, the NPC converter is the best alternative.
Table 3. Comparison table for DC-AC converter topologies.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Simulation Software</th>
<th>Output Power P (kW)</th>
<th>Input Voltage V&lt;sub&gt;AC&lt;/sub&gt; (V)</th>
<th>Output Voltage V&lt;sub&gt;dc&lt;/sub&gt; (V)</th>
<th>Switching Frequency f&lt;sub&gt;sw&lt;/sub&gt; (kHz)</th>
<th>Inductor L (µH)</th>
<th>Capacitor C&lt;sub&gt;1&lt;/sub&gt;/C&lt;sub&gt;2&lt;/sub&gt; (µF)</th>
<th>Performance and Quality</th>
<th>Topology</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30-2L</td>
</tr>
<tr>
<td>[19]</td>
<td>PSIM</td>
<td>50</td>
<td>400</td>
<td>800</td>
<td>100</td>
<td>500</td>
<td>3000</td>
<td>Efficiency (%)</td>
<td>97.87</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
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<td>Total losses (W)</td>
<td>1062</td>
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<td></td>
<td></td>
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<td>1896</td>
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<td></td>
<td></td>
<td>1428</td>
</tr>
<tr>
<td>[36]</td>
<td>PLECS</td>
<td>22</td>
<td>400</td>
<td>800</td>
<td>20</td>
<td>750</td>
<td>-</td>
<td>Efficiency (%)</td>
<td>98.86</td>
</tr>
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<td></td>
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<td></td>
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<td>Total losses (W)</td>
<td>256.48</td>
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<td>351.81</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>237.16</td>
</tr>
<tr>
<td>[37]</td>
<td>MATLAB</td>
<td>2</td>
<td>50</td>
<td>200</td>
<td>15</td>
<td>300</td>
<td>9020</td>
<td>Efficiency (%)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>Total losses (W)</td>
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<td>-</td>
</tr>
</tbody>
</table>

4.2. DC-DC Power Converters

The adaptation of the output voltage of the AC-DC converter to the battery voltage is achieved by the second stage: the DC-DC converter. This stage is accountable for charging the battery electric vehicle, according to a specific charging method, while ensuring safe operation of the battery by communicating with the BMS.

If galvanic isolation is ensured by the power transformer, a non-isolated DC-DC converter can be employed as a second stage. Figure 6 shows a charging station with three ultra-fast chargers, each with a power of 350 kW, with galvanic isolation provided by a MV/LV transformer with a power of 1250 kVA.

Figure 6. Three ultra-fast chargers isolated by a MV/LV transformer.
As the battery voltage is less than the output voltage of the rectifier in many applications, the Buck converter illustrated in Figure 7a can be used to decrease the input voltage, but this is not practical for high power applications because the current is transported by a unique switch [38]. In addition, the size of the filtering inductor will be high if low current ripple is desired [39].

![Figure 7. Non-isolated DC-DC converter topologies for electric vehicle ultra-fast charging application: (a) buck DC-DC converter; (b) three-phase interleaved DC-DC buck converter; (c) buck-boost DC-DC converter; (d) three-phase interleaved DC-DC buck-boost converter.](image)

As an alternative to using an oversized single-phase converter, three-phase interleaved DC-DC buck converters are suitable for high-current applications thanks to their ability of sharing the output current between three phases, allowing the reduction in lower filtering inductors and smaller semiconductor switches. In addition, the efficiency of the power converter is generally higher because the fundamental frequency is multiplied by three, which results in a high frequency of the system, a better transient response, a low current ripple, and a reduced size of output filters [40]. As presented in Figure 7b, the three-phase interleaved DC-DC buck converter has a simple structure. Hence, this converter has been well explored in the literature for electric vehicle charging applications [41,42]. Nevertheless, as the number of phases grows, the number of power interrupters, cost, difficulty of the control system, and power density also grow [43].

If bidirectional power flow is needed, and the power exchange is requested between the electric vehicle storage device and the grid (V2G), the buck-boost converters illustrated in Figure 7c,d can be used for charging stations [44].

A comparative study of non-isolated DC-DC converters is presented in Table 4. As it can be noticed in this study, the voltage ripple of the two-phase interleaved DC-DC buck converter is low compared to the classical buck converter. Thus, the interleaved converters reduce the voltage ripple, which can increase the battery lifetime in an electric vehicle. Similar to the voltage ripple, the current ripple can be reduced if the interleaved converter is employed. This can improve the efficiency of battery charging and reduce the size of the filtering inductor [45].

<table>
<thead>
<tr>
<th>Topology of Converter</th>
<th>Voltage Ripple (V)</th>
<th>Current Ripple (A)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional DC-DC buck</td>
<td>$1.084 \times 10^{-2}$</td>
<td>$1.196$</td>
<td>98.99</td>
</tr>
</tbody>
</table>

If the ultra-fast charger is plugged directly to the LV grid, a galvanic isolation is required to ensure operational safety rules. Hence, a DC-DC converter is galvanically isolated using a transformer.

Figure 8a depicts the basic topology of the Phase-Shift Full Bridge (PSFB) converter. It consists of an H-Bridge with power switches in the primary of the transformer, and usually a diode bridge in the secondary connected to the battery electric vehicle. For this reason,
this converter provides only unidirectional power transfer [46]. It is possible to perform zero-current switching (ZCS) or zero-voltage switching (ZVS). Hence, the PSFB converters can deliver a very high-power rating and high output voltage [47].

![Figure 8. Isolated DC-DC converter configurations for electric vehicle ultra-fast charging application: (a) Phase-Shift Full Bridge (PSFB) converter; (b) LLC resonant converter; (c) Dual Active Bridge (DAB) converter.](image)

The LLC resonant converter, as depicted in Figure 8b, has a resonant LLC tank, which consists of a resonant capacitor, a resonant inductor, and the magnetizing inductance of the high-frequency transformer. This isolated converter provides excellent efficiency and a high-power density and is widely used for ultra-fast charging [48]. The soft-switching techniques are also employed, whether ZVS turn-on or ZCS turn-off [49].

The work developed in [50] provides a comparative study between the LLC resonant converter and the PSFB converter during total charging and the CC-CV charging process of the battery. Table 5 shows that the PSFB converter is the best isolated DC-DC converter thanks to its low losses, good efficiency, and low cost.

![Table 5. Comparison table for LLC resonant converter and PSFB converter.](image)

If bidirectional energy flow is needed, a Dual Active Bridge (DAB) converter, as illustrated in Figure 8c, can be employed for electric vehicle charging systems. However, the control of the eight power switches is more complex, and the non-resonant operation results in a slightly lower efficiency at lower power [51].

4.3. Industrial Applications

As seen in Figure 9, the modular 50 kW power cell designed by Semikron has an input Vienna rectifier and a PSFB converter for an output voltage up 1000 V. It is developed for easy paralleling to meet 350 kW and make it possible to recharge an electric vehicle in 11 min [52]. Figure 10 shows an example of the topology proposed by Infineon Technologies for a 30 kW converter to be combined for the realization of a unidirectional very high power charger. This charger consists of a Vienna rectifier followed by an LLC resonant converter [53]. Another example based on a three-phase two-level rectifier and three-phase interleaved DC-DC buck-boost power converter is illustrated in Figure 11, where ABB’s
Terra High Power Series is used. These fast chargers achieve 150 kW by the unit, while each unit is composed of 50 kW modules, with galvanic isolation ensured by a power transformer. To achieve increased power levels, this unit is multiplied many times to attain a maximum of 600 kW for electric trucks and electric buses [54].

![Figure 9. Modular 50 kW power cell (Designed by Semikron).](image)

![Figure 10. Modular 30 kW charger (proposed by Infineon Technologies).](image)

![Figure 11. Modular 50 kW charger (designed by ABB).](image)
5. Modular Design Approach

In the literature, there are many studies that deal with energy conversion systems consisting of several identical converters operating in series/parallel configurations [55,56]. This modular approach has several advantages. Firstly, it allows the manufacturer to achieve economies of scale by using the same blocks for different charging powers, whether on-board or as an external charger. Semiconductor manufacturers offer complete stages in packages integrating control, thermal protection and power semiconductors, up to 350 kW [57]. Furthermore, in the event of a fault, it is possible to isolate the faulty block and ensure continuity of operation in a degraded mode [58]. In addition, the vehicle is charged at maximum power for a brief period. Once the charging power drops below half the maximum power of the charging station, a modular charger can assign modules to charge another vehicle [59].

As shown in Figure 12, an ABB’s Terra HP charging system has an output voltage ranging from 150 to 920 V and an output current ranging from 0 to 500 A. It is therefore difficult to operate a single converter with high performance across this wide load range. However, it is easier to increase the number of small power active converters in a modular configuration depending on the load demand. On the other hand, this charger has the possibility to switch from one 350 kW charge to two 175 kW charges, as depicted in Figure 13, which allows better exploitation of the installed capacity of the installation by adding more simultaneous users [60].

![Terra HP 350 output load and operational curve.](image)

**Figure 12.** Terra HP 350 output load and operational curve.

![Modular 50 kW charger (designed by ABB).](image)

![Modular 50 kW charger (designed by ABB).](image)

**Figure 13.** (a) Max charging dedicated to premium electric vehicle at up to 350 kW on either charge post; (b) shared power delivery for premium electric vehicle utilization at up to 175 kW to each vehicle.
6. Integration of Ultra-Fast Chargers into Standalone Microgrids

Standalone microgrids are small electrical grids designed to supply power to areas where there is no connection to the main distribution grid. These isolated microgrids are based on solar energy, wind power, generators, and battery storage [61]. Microgrids can be designed to provide AC or DC power. Each case has its own characteristics with advantages and disadvantages.

For AC microgrids, the current supplied at the bus level, which is connected to the various energy resources, storage systems, and loads, is an AC electric current. In this case, the ultra-fast charger is composed of two converters (AC-DC and DC-DC). This topology is characterized by the ease of changing voltage levels; fault detection is very manageable with a wide choice of protection equipment. Production and development costs are very low due to the maturity of this technology [62]. However, this architecture increases the number of converters [63]. Figure 14 shows an example of an AC microgrid in which the ultra-fast charger is composed of two stages.

Figure 14. The ultra-fast charging station in AC standalone microgrid.
For DC microgrids, the current supplied at the bus level, which is connected to the various energy resources, storage systems, and loads, is a DC electric current. Thus, the ultra-fast charger consists of a single converter (DC-DC). In this topology, the number of DC-AC conversions is reduced, and their losses are minimized [64]. Frequency and reactive power are not controlled, and harmonic distortions are not imposed [65]. However, the architecture of DC microgrids requires a large redesign of the existing power grids, which makes the implementation cost considerably higher [66]. Protection technologies are not yet developed and are not cost effective [67]. Figure 15 shows an example of a DC microgrid in which the ultra-fast charging system consists of a single stage.

![Diagram of DC microgrid](image)

**Figure 15.** The ultra-fast charging station in DC standalone microgrid.

The massive deployment of ultra-fast charging stations will increase power consumption, losses in DC or AC lines and power converters, and additional voltage drops, which can vary according to the penetration rate of ultra-fast charging stations in the standalone microgrid. This effect will also decrease the reliability and quality of the electric power supplied to the eventual consumers [68]. The two solutions for deploying ultra-fast charging stations are either to reinforce the standalone microgrid infrastructure and increase energy production or to seize the opportunities of EVs through V2µG technologies and the coordination of electric vehicle charging. The latter solution appears to be the least costly [69]. V2µG technology optimizes the integration of renewable energies by storing the surplus energy produced during periods of strong wind and sunshine, and re-injecting this excess energy into the microgrids as required. In addition, this technique reduces the economic impact by relieving the microgrids during peak periods [70,71]. V2µG also makes it possible to remunerate drivers for the services they provide with their batteries [72].
7. Advanced Control Techniques for Ultra-Fast Chargers Integrated into Standalone Microgrids

The control of ultra-fast chargers must meet several objectives. The controller of AC-DC converters provides power factor correction, DC voltage regulation, robustness to load and power grid variations, and neutral point voltage balance of the AC-DC converter if it is three-level. Moreover, the regulator of the DC-DC stage ensures safe battery charge during $\mu$G2V by applying the previously discussed methods of fast charging (CC-CV and MSCC). If the ultra-fast charger is bidirectional, the DC-DC stage also ensures a safe discharge of the battery during the V2$\mu$G mode.

A control structural scheme of the ultra-fast charger integrated into the AC standalone microgrid is presented in Figure 16. In the AC-DC stage, a neutral point balance controller is applied to the SVPWM algorithm in order to balance the voltages of the AC-DC converter’s two output capacitors, which allow a stable DC voltage to be delivered to the DC-DC converter and decrease the harmonic content injected into the electrical power grid [73]. In addition, the voltage outer loop regulator adjusts the DC output voltage $V_{dc}$ to its reference $V_{dc}^{ref}$. The current inner loop is used to achieve the unity power factor. For this reason, the reference of the reactive current is equal to zero ($i_{qref} = 0$) and the reference of the active current $i_{dref}$ is produced by the voltage outer loop controller [74]. In the DC-DC stage, the current loop controller is developed in order to regulate the battery current $I_B$ to its desired value $I_B^{ref}$. This later is established during the CC stage. On the other hand, the voltage loop regulator is designed so that the battery voltage $V_B$ tracks the reference $V_B^{ref}$ during the CV stage [75]. The BMS delivers current and voltage references to the electric vehicle’s ultra-fast charger controller. If the DC-DC converter is bidirectional, it can include an inner battery current control loop for the discharging mode (V2$\mu$G). For DC microgrids, the charger will only consist of a DC-DC converter. The control scheme in this case is illustrated in Figure 17.

Figure 16. A control structural scheme of the ultra-fast charger integrated into the AC microgrid.

Figure 17. A control structural scheme of the ultra-fast charger integrated into the DC microgrid.

Linear control techniques are widely applied to ultra-fast chargers thanks to their flexibility of adjustment, the practical implementation, and the simplified structure. Various types of linear controllers are available: Proportional Integral (PI) control technique, Proportional Resonant (PR) controller, Proportional Integral Derivative (PID) controller, Linear Quadratic Regulator (LQR) control algorithm, etc. Table 6 summarizes the various linear control techniques that have been proposed for ultra-fast chargers in the literature.
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Figure 16. A control structural scheme of the ultra-fast charger integrated into the AC microgrid.

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Table 6. Linear control techniques proposed for ultra-fast chargers in the literature.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Topology</th>
<th>Control Strategy</th>
<th>Simulation Software</th>
<th>Experimental Validation?</th>
<th>Objectives of Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>[76]</td>
<td>NPC</td>
<td>DAB</td>
<td>PI</td>
<td>PSIM</td>
<td>No</td>
</tr>
</tbody>
</table>

(1) Ensure a power factor unity;
(2) Absorb/inject a power current with a low THD;
(3) Regulate the current delivered to or from the battery according to its state of charge (SOC);
(4) Adjust the difference between the DC voltage injected by the rectifier and the battery voltage.
<table>
<thead>
<tr>
<th>Ref.</th>
<th>Topology</th>
<th>Control Strategy</th>
<th>Simulation Software</th>
<th>Experimental Validation?</th>
<th>Objectives of Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>[77]</td>
<td>Vienna LLC</td>
<td>PI</td>
<td>-</td>
<td>Yes</td>
<td>(1) Neutral point potential balance of the rectifier; (2) Perform power regulation and power factor correction; (3) Frequency conversion and phase shift hybrid regulation; (4) Constant voltage and constant current controls of the LLC converter.</td>
</tr>
<tr>
<td>[78]</td>
<td>NPC</td>
<td>Three-phase Interleaved buck-boost</td>
<td>PI</td>
<td>Simulink</td>
<td>Yes</td>
</tr>
<tr>
<td>[79]</td>
<td>3θ-L2</td>
<td>Three-phase Interleaved buck-boost</td>
<td>PI</td>
<td>Unknown</td>
<td>No</td>
</tr>
<tr>
<td>[80]</td>
<td>Vienna DAB</td>
<td>PI</td>
<td>Simulink</td>
<td>No</td>
<td>(1) Safe charging of the BEV using CC-CV method; (2) Power factor correction; (3) Reducing the THD$_i$ to 0.79%; (4) Improve the efficiency of the charging system; (5) Large voltage range of the charger (48–600 V).</td>
</tr>
<tr>
<td>[81]</td>
<td>Vienna LLC</td>
<td>PI</td>
<td>Simulink</td>
<td>No</td>
<td>(1) Excellent performance during CC-CV charging process; (2) Reducing the THD$_i$ to 3.12%; (3) Achieve good soft-switching.</td>
</tr>
</tbody>
</table>

The linear control techniques are based on the linearization model. However, the ultra-fast chargers of BEVs are power electronic converters consisting of power switching devices, which are nonlinear components [82]. It is therefore not easy to guarantee that the ultra-fast charger has an excellent dynamic performance. In this context, nonlinear control strategies are key to improving the dynamic performance and robustness of ultra-fast chargers [83]. These last few years, the sliding mode (SMC) controller, backstepping (BSC) approach, feedback linearization (FBL) control technique, model predictive (MPC) control method, and fuzzy logic (FLC) control method have been used in power electronics converters so as to meet the control performance requirements of the converter in various applications [84]. The performance comparison of the nonlinear control strategies applied to the power converters studied in [82,85–88] is summarized in Table 7.
### Table 7. Performance comparison of the nonlinear control strategies applied to the power converters.

<table>
<thead>
<tr>
<th>Control Method</th>
<th>Robustness to Disturbance</th>
<th>Robustness to Uncertainties</th>
<th>Response Time</th>
<th>Algorithm Complexity</th>
<th>Main Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMC</td>
<td>Good</td>
<td>Good</td>
<td>Fast</td>
<td>Medium</td>
<td>(1) Chattering problem; (2) The stability is ensured by using the Lyapunov function.</td>
</tr>
<tr>
<td>BSC</td>
<td>Poor</td>
<td>Medium</td>
<td>Fast</td>
<td>High</td>
<td>(1) The complex choice of coefficients; (2) The stability is ensured by using the Lyapunov function.</td>
</tr>
<tr>
<td>FBL</td>
<td>Medium</td>
<td>Poor</td>
<td>Fast</td>
<td>Medium</td>
<td>(1) The possibility of using linear control techniques; (2) Parametric variations cannot be controlled.</td>
</tr>
<tr>
<td>MPC</td>
<td>Medium</td>
<td>Medium</td>
<td>Normal</td>
<td>Medium</td>
<td>(1) Uses significant computing power; (2) Detailed description of the model.</td>
</tr>
<tr>
<td>FLC</td>
<td>Good</td>
<td>Poor</td>
<td>Slow</td>
<td>Medium</td>
<td>(1) Uses significant computing power; (2) Does not require mathematical model.</td>
</tr>
</tbody>
</table>

### 8. Conclusions

This work addressed ultra-fast charging stations for electric vehicles, where the charger is outside the electric vehicle and has a charging power of up to 350 kW. This makes it possible to limit the charging time. These chargers are in accordance with international standards and methods to ensure fast and safe battery charging. Additionally, a comparative study of the different topologies of ultra-fast chargers as well as some industrial designs were discussed. Moreover, the paper discussed the advantages of the modular design of ultra-fast chargers. The integration of ultra-fast chargers into standalone microgrids using V2µG technology is also discussed in this review. Finally, advanced control strategies of the rectifiers and DC-DC converters in DC and AC standalone microgrids are studied in order to improve the dynamic performance and robustness of ultra-fast chargers. Consequently, this document is a useful guide for researchers and engineers who intend to select the appropriate topology of the converter and develop advanced controls for ultra-fast chargers.

### Author Contributions:

This document is the result of a collaboration between the authors. Conceptualization, A.S. and M.O.; methodology, A.S. and M.O.; software, A.S.; validation, M.O. and M.M.; formal analysis, A.S. and M.O.; investigation, A.S., M.O. and M.M.; resources, A.S. and M.O.; writing—original draft preparation, A.S.; writing—review and editing, A.S. and M.O.; supervision, M.O.; funding acquisition, M.O. and M.M. All authors have read and agreed to the published version of the manuscript.

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