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# Interface Converters for Residential Battery Energy Storage Systems: Practices, Difficulties and Prospects

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**Abstract:** Recent trends in building energy systems such as local renewable energy generation have created a distinct demand for energy storage systems to reduce the influence and dependency on the electric power grid. Under the current market conditions, a range of commercially available residential energy storage systems with batteries has been produced. This paper addresses the area of energy storage systems from multiple directions to provide a broader view on the state-of-the-art developments and trends in the field. Present standards and associated limitations of storage implementation are briefly described, followed by the analysis of parameters and features of commercial battery systems for residential applications. Further, the power electronic converters are reviewed in detail, with the focus on existing and perspective non-isolated solutions. The analysis covers well-known standard topologies, including buck-boost and bridge, as well as emerging solutions based on the unfolding inverter and fractional/partial power converters. Finally, trends and future prospects of the residential battery storage technologies are evaluated.

**Keywords:** residential energy storage; battery energy storage systems; standards; grid interface converters; intellectual property; bidirectional converters; AC-DC power converters; DC-DC power converters; multilevel converters; partial power converters

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## 1. Introduction

Consumption of resources as well as their collection and processing are usually uneven. First of the all, it involves energy resources, traditionally, food and various fissile fuels. Nowadays, the necessity to store energy has gained new forms that are applied to the energy resources, specific for the dedicated technology equipment. This, in particular, regards electrical engineering, the rapid development of which during the last two centuries has formed the demand for storages of electrical energy even at the level of residential applications. During recent years, this tendency has become more topical due to several reasons. Firstly, renewable energy sources are in much wider use. In addition, this use is obliged by some administrative regulations like EU directives [1–3]. In spite of the irregular generation profile, the renewable energy sources are being installed even at the households. Secondly, the range and number of various household devices have expanded. There exist plenty of storages dedicated to electrical energy [4]. For example, it is possible to convert electrical energy into chemical (in the form of pure hydrogen) by means of electrolysis and then back—by means of a fuel cell [5]. However, in spite of the most recent achievements in the field of fuel cells [6,7] and development of converter technologies for fuel cells [8], the most functional, reliable and energy efficient equipment for electrical energy is an electrochemical battery energy storage (BES) system.

The constantly increasing number of papers (Figure 1) devoted to battery energy storage systems (BESSs) proves the importance of these energy storage devices in various applications. These papers address all aspects of their use, but particular attention is paid to the interface converters of BESSs. The numerous review papers devoted to this topic [9–12] describe a generalized state of the art in this field. Typically, they evaluate which converter schemes are more energy efficient, with a reduced component count and lower voltage/current stresses. At the same time, the role and peculiarities of the interface converters in the context of the BESS structure are usually not clear-cut and detailed in these reports.

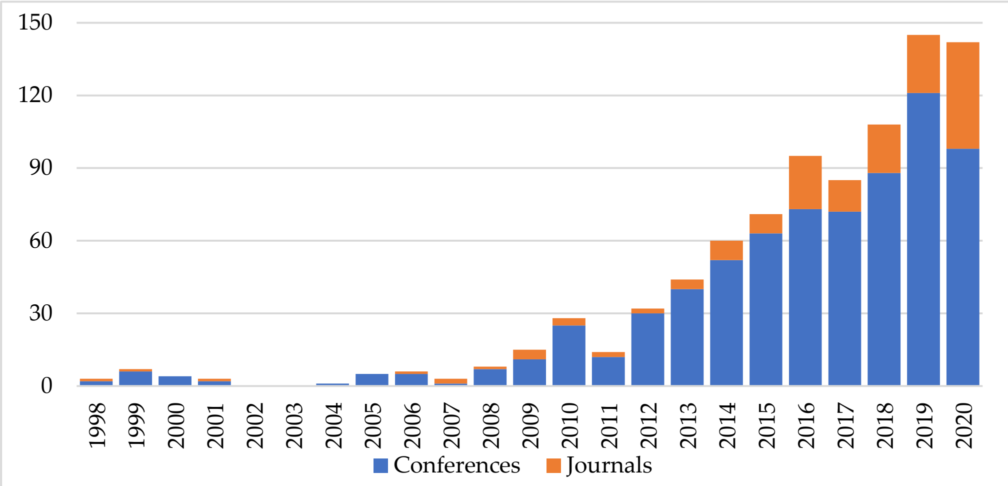



**Figure 1.** Number of recent IEEE publications about BESS.

BESSs nowadays are also readily commercially available. The analysis of the market of household electrical equipment [13,14] shows that numerous BESSs are already available as a market offering. On the one hand, the variety of their parameters and operation conditions provides wide choices; on the other hand, it makes the choice more complicated for the final users of BESS and complicates the development of the interface converters for different BESSs. In addition, the elaboration and commercialization of BESSs and their interface converters have a strong link to the market of some renewable energy sources and pure electric vehicles, which may not only act as BESSs, but also, after their recycling, provide high voltage (HV) second-life Li-ion batteries for use in BESS [15,16].

The goal of this work is to analyze the majority of interface converters in the context of the corresponding BESSs, their operation conditions (standards, energy tariffs, subsidies and other elements of energy policy), BESS market trends and after this analysis, to formulate prospective development directions of the BESS interface converters. In particular, this regards the converter schemes for HV batteries.

The rest of the paper is organized in five sections. Section 2 reviews the motivating factors of the BESS study: battery technologies, their applications, as well as standards and other regulations that may regard this work. Section 3 briefly analyzes the commercially available BESSs, trying to emphasize their internal structure. Section 4 provides a broad analysis of converter technologies applicable to BESSs. Section 5 discusses the previously analyzed equipment and technologies in the context of BESS development. Finally, the conclusions are given in Section 6.

## 2. Motivation and Driving Factors for Use of Battery Energy Storage Systems

### *2.1. Development of Electrochemical Energy Storages*

The most intensive development of electrochemical batteries has taken place since the late 20th century and it is still progressing. Due to the constantly growing demand for portable electronics, vehicular technologies and energy systems, the battery technologies of known electrochemistry have been "polished" and new technologies have been introduced to the market. Presently, the most significant commercially available battery technologies are [17,18]: advanced lead-acid (LA), nickel-oxyhydroxide (NiMH), sodium–sulfur (NaS), various kinds of Li-ion batteries, as well as redox flow batteries (RFBs), in particular, vanadium redox batteries (VRBs) [18]. LA technology, the oldest among them, is still the cheapest as well as quite energy efficient (up to 85%). The drawbacks of LA batteries are rather low specific energy (Figure 1) and low number of charge-discharge cycles (lifetime). Historically, the next successive NiMH technology (replacement for NiCd) is characterized by average specific power, specific energy and lifetime, but undergoes significant self-discharge and is of low charge-discharge efficiency (65%). The NaS batteries are of high specific energy, energy efficiency and lifetime (90% and 4000 cycles, respectively [18]), but their operation temperature is high—they require heating, which makes them impractical in many cases. Today, the most quickly developing battery technology is the Li-Ion. Its high specific energy, specific power (Figure 2), lifetime (up to 10k cycles), energy efficiency (up to 95%) achieved at reasonable price makes the technology very suitable for use in portable electronics, all-electric vehicles, household energy systems, and, even, in energy distribution grids [19]. However, the specific parameters of Li-Ion batteries depend on relevant chemistry and all advantages are typically not concentrated in one device. Finally, RFBs, in particular VRBs, are the batteries that utilize reduction–oxidation reaction between two liquids, which occurs through a membrane. The liquids are pumped to the membrane that makes RFBs similar to fuel cells, where the liquids are chemically restorable. The main advantage of these batteries is their potentially infinite lifetime. Lastly, it must be mentioned that modern batteries are not just a series connection of galvanic cells. They often include electronics for balancing, management and protection as well as chargers in some cases. Therefore, these batteries can be considered as complex complete energy units for immediate use [20–22].

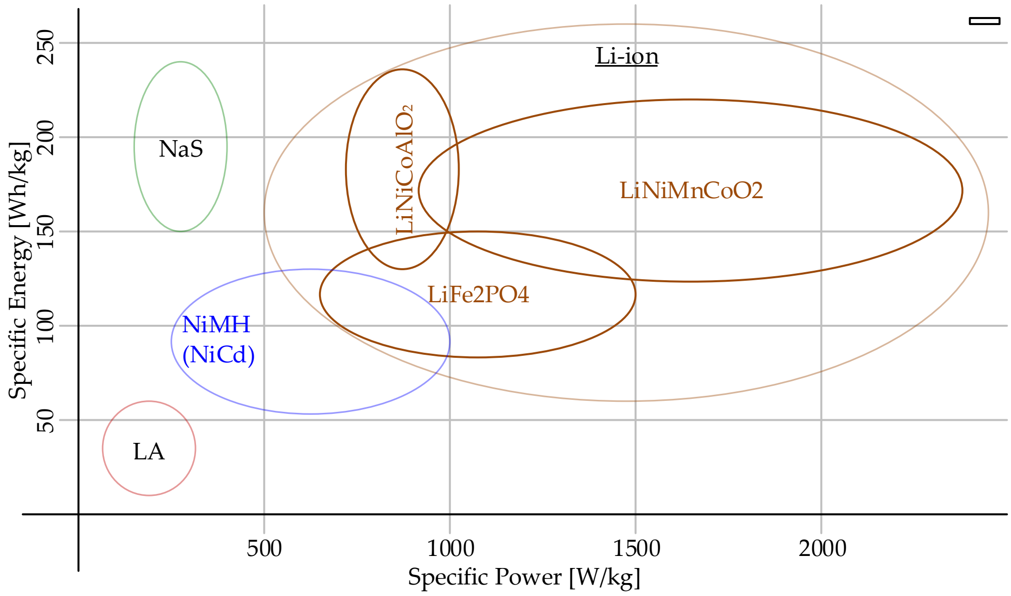



**Figure 2.** Specific energy and specific power of the commercially available batteries (based on data from [18]).

### 2.2. Extensive Use of Battery Energy Storages in Transport

One of the recent global societal and legislative tendencies on the national and international levels is the request to reduce the consumption of fossil fuels and to increase the efficiency of energy consumption [3,23]. Among other areas, this involves vehicular technologies as well. Regarding ground vehicles, this initiative means wider use of plug-in electric vehicles (PEVs) or all-electric vehicles (AEVs) and hybrid ones, equally in the public and private sectors. In [24,25], the availability of cost-effective batteries of several hundred volts for main electrochemical energy storage of PEV is reported. More recent papers [26–29] consider these PEV storage systems valuable enough to be a part of the energy supply grid. Further development of the BESs makes their use possible in larger ground vehicles—first of all, in the public transport [30,31].

Better BESs are also required for water vehicles, first of all, for smaller auxiliary vehicles—boats, yachts, water buses, etc. For example, in [32], the electrification of the water buses in Venice is considered as a successful example of BES use in water transport. At the same time, with regard to bigger ships and vessels, the role of BESs differs with time. While earlier configurations of marine energy systems utilize high voltage batteries for stabilizing the traditional on-board AC grid and power smoothing [33,34], modern systems also take into account the possibility of all-electric propulsion of the ship [34,35].

Finally, the most advanced BESs are applicable in aircraft. The traditional electrical supply of an aircraft combines an AC and DC grid. Better performance of the applied batteries leads to a better quality of the 28 V DC grid [36,37]. At the same time, top BES technologies allow production of extremely light batteries that enable all-electric aircraft [38].

In conclusion, the extensive use of batteries in transport, in particular, the growing number of light PEVs, high capacity of their batteries and huge capacity of these batteries in total, as well as their wide distribution, make these BESs a substantial grid resource for storing energy. These BESs and their interface converters are typically high-voltage devices, but the corresponding solutions of the interface converters can be adopted for residential use.

### 2.3. Recent Challenges in the Field of Power and Energy Supply

The request to reduce fossil fuel consumption [3,23] regards also power distribution and supply networks. For the power and energy supply systems, this means that the burning of fossil fuels must be substituted with renewable energy generation. In turn, the main properties of renewable energy generation are:

(1) Uneven generation profile—regardless of the kind, the renewable energy sources typically do not provide constant power. In particular, the generation of PV panels depends on solar irradiation and varies with the daytime, cloudiness, season, location of PV and solar activity. The generation of wind turbines depends on the wind strength, which is unique for its location, season and occasional weather fluctuation. The generation of hydro and waves turbines depends on the amount of water that is a long-term function of seasonal and global weather changes.

(2) Variety of power ratings and types of energy sources exist even within the same group. For example, the power of PV depends on the local properties and financial abilities of a particular household.

(3) Variety of allocation of the renewable energy sources—depending on the particular economic conditions and policy of energy operator, these sources may be allocated differently.

Altogether, this makes renewable energy generation less stable and reliable. This, as well as several other problems [9,39–43], can be solved with the help of Battery Energy Storage Systems (BESSs).Figure 3 shows the use of BESSs in energy applications.

When considering a BESS in a small household with different loads and renewable energy sources, it is very important to smoothen renewable energy generation—providing storage for excessive renewable or cheap grid energy [44–46]. The BESS is also capable of performing the function of an uninterruptible power supply. This is the main function in the case of islanded residential grids [47–49]. At very uneven loads, the BESS may also smoothen the real-time loading of supply equipment—transformers and lines.

In the distribution grids, the functions of the dedicated BESS are similar but more specified. Price compensation now can be considered as a complete function of energy trading, smoothening of power generation regards not only renewables, but smoothening of consumed power at this level saves the capacity of distribution equipment. Additionally, BESS in distribution grids may perform grid service functions: grid black restart as well as voltage and frequency regulation [39,50]. The choice of BESS parameters is a subject of multiple factors [51]: standards, power losses, voltage of majority of available PEVs, compatibility with pure resistive loads.

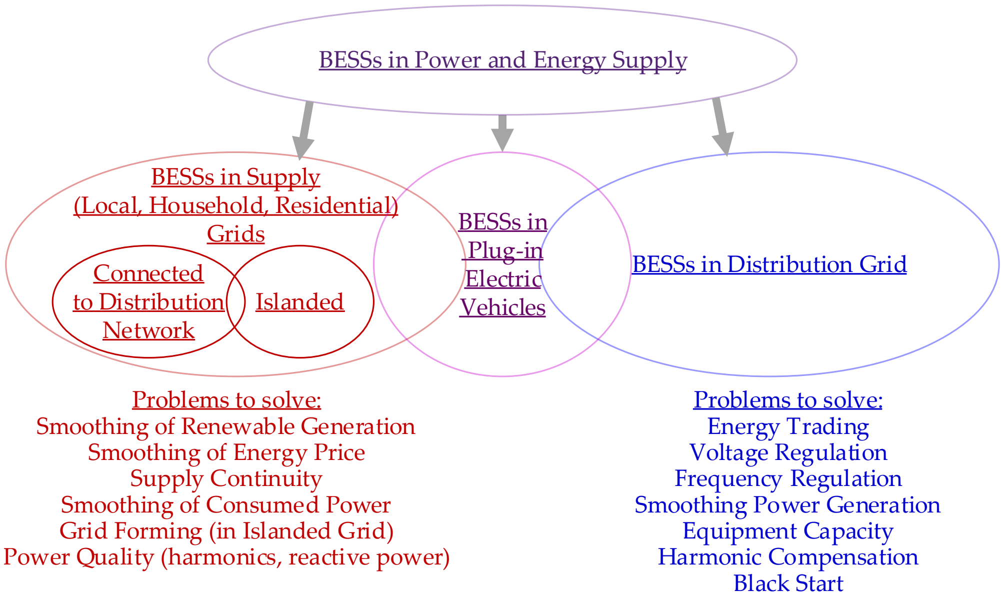



**Figure 3.** Battery Energy Storage Systems (BESSs) in power and energy supply at a glance.

### *2.4. Standards and Other Regulations Applicable to Battery Energy Storage Systems*

The standards directly related to the electrical energy storage systems of households are still under development. In Europe, this is being done by the IEC 120 committee group [52]. They have developed a roadmap for developing standards, which is planned to be completed by the end of 2023. Until that date, European manufacturers have to use general standards for the production of power converters, in particular, power interfaces for alternative energy sources and uninterruptible power supply (Table 1).

**Table 1.** Summary of Standards and Regulations applicable to BESS.

| Reference | Application Area of the Standard |
|---|---|
| [53] | USA, Converter housing and selection of components |
| [54] | IEC, Classification of BESS locations in households |
| [55] | IEC, Voltage inverters for high voltage DC networks |
| [56] | IEC, Controlling of converters in microgrids |
| [57] | IEC, Connection of PV to the grid and requirements for electromagnetic compatibility parameters |
| [58] | IEC, Bidirectional low voltage (up to 1000 V AC and 1500 V DC) converters connected to the grid and description of the terms used in these networks |
| [59,60] | IEC, Test methods and acceptable parameters for low voltage uninterruptible power supplies |
| [61] | IEC, Disposal of converters of uninterruptible power supplies |
| [62] | USA, Safety regulations within data centers and telecom central offices |

In the USA, a universal standard has been developed that describes the operation of electrical energy converters in distributed networks. With regard to BESS, the manufacturers also have to apply general standards for converters. This includes standards for interface converters of energy storage. In addition, in the USA, the parameters of batteries are defined and standardized and based on the standards of telecommunication equipment (Table 1).

## 3. Commercially Available Residential Storage Systems

In this section, the BESs available on the market are analyzed taking into account the parameters available from the product datasheets or application manuals. Despite the market for such devices still being dynamic, some common properties and features can already be distinguished as common practice in the field.

### *3.1. Typical Example of Battery Energy Storage Systems Dedicated to Household Applications*

The Tesla Powerwall 1 (3.3 kW/6.4 kWh) was one of the first attempts to include BESS into a household energy system and has been available on the market since 2015. It operates with a DC-bus and, in general, has to be installed in conjunction with a grid inverter, which is sold separately.

This precluded its use as a completely independent BESS, reduced market prospects and shortly led to its replacement by the Tesla Powerwall 2 (5 kW/13.2 kWh) [63]. In contrast to the previous model, the Powerwall 2 (Figure 4a) includes an AC inverter and can be connected directly to the AC grid. This enables its use as a residential BESSs, regardless of the renewable generation source (solar panels or a wind generator). Therefore, the functional features of Powerwall 2 have expanded significantly, including the possibility of stand-alone operation without grid connection (islanded mode). For normal operation, it requires an additional commutation unit called "energy gateway" and its full cycle efficiency is 90%.

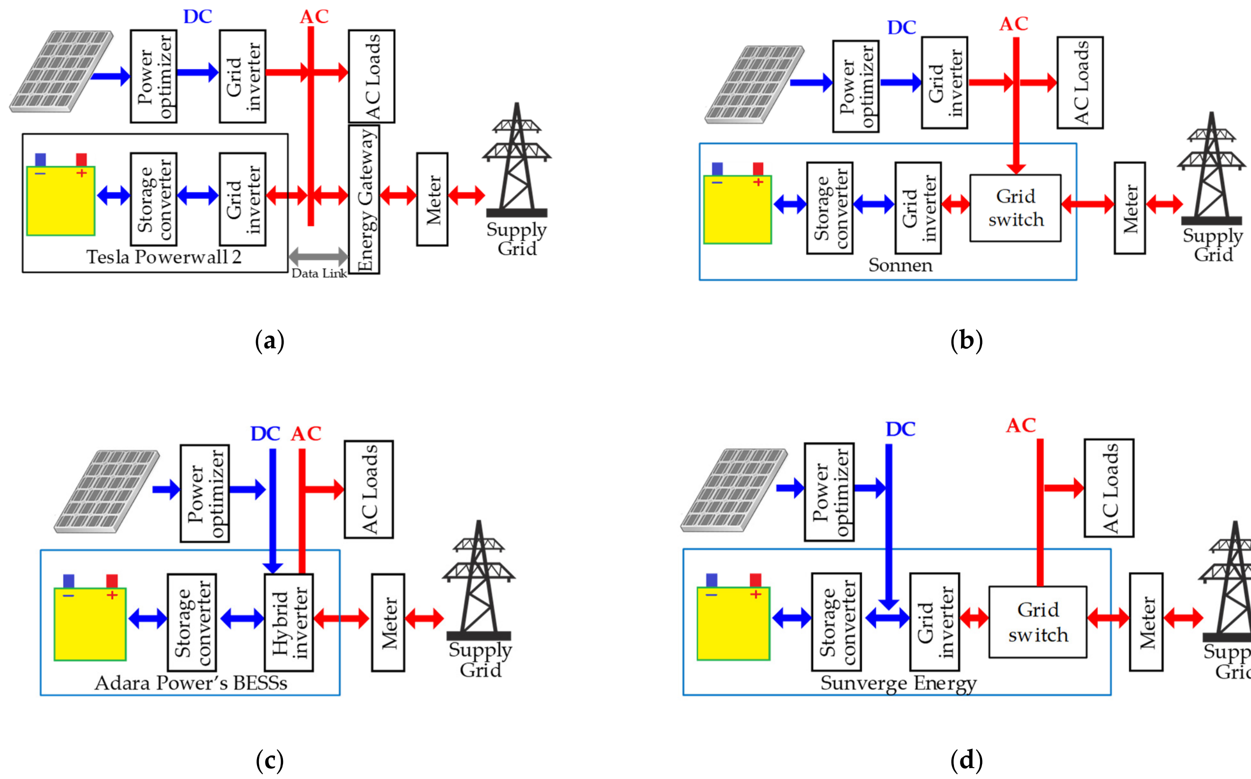



**Figure 4.** Typical examples of system configurations of different BESs: (**a**) Tesla Powerwall 2, (**b**) SonnenBatterie, (**c**) Adara Power-Residential and (**d**) Sunverge energy.

Sonnen is another early market player that began offering its residential BESSs in December 2015 [64]. These BESSs are designed for households with solar and wind power generators providing energy storage and backup power. They are available in two versions, with a built-in inverter for PVs (hybrid output) and without it (eco output). In Germany, the company launched a coordination network that brings together power producers and storage owners. This service allows the participants resided in the same network to exchange electricity with each other, exporting surplus to the grid. Currently, this service has over 10,000 users. With $LiFePO_4$ batteries in its system, the manufacturer claims an output power of 2.5–3.3 kW in the "eco output" version and 5.5 kW in the "hybrid output" version. The energy capacity of the base model is 5 kWh with the ability to increase it up to 15 kWh in 2.5 kWh steps. The manufacturer promises a 98% maximum efficiency of the batteries and a 96% efficiency of the converter, which gives a total cycle efficiency of around 88.5%. The internal topology of SonnenBatterie and SonnenFlat is not disclosed, but the structural diagram of their operational environment (Figure 4b) shows that it is connected to the main supply grid as well as to the secondary grid formed by the solar panel inverter through an automatic transfer switch (ATS). This enables a SonnenBatterie to operate in an uninterruptible power supply mode.

Enphase Energy is another company that entered the residential storage market with its "AC Battery" in 2015. It is a very compact (0.27 kW/1.2 kWh) modular system that can be used in conjunction with micro-inverters and the "Envoy-S gateway" [65]. Later, the company's storage portfolio was extended with the Encharge 3 (1.28 kW/3.3 kWh) [66] and Encharge 10 [67], which is composed of three of the former units. According to the datasheet information, the cycle efficiency of a newer Enphase product is 89% at half power. Backup power from the battery can be provided using an additional microgrid interconnection device.

Other notable market players are Victron Energy with a range of products like Easy Solar and MultiPlus [68]; Adara Power's Residential [69,70] coupled with an inverter from Schneider Electric (Figure 4c) [71] and Sunverge Energy (Figure 4d) [72]. Moreover, one of the key market players is the battery manufacturer LG Chem [73], who is offering its low- and high-voltage battery modules for integration with SMA, Fronius, SolarEdge, and Huawei inverters/chargers.

### *3.2. Summary of Parameters and Features of Commercial Residential BESs*

Due to the market dynamics, with both large and small companies are entering and leaving the market continuously, so it is hard to determine a global leader in the area. Moreover, some of the products currently have a limited proposal or are available only in certain regions. The typical price for typical residential BESs is currently in the range of 1–2 kEUR/kWh (Table 2). Technical information on these products is mostly limited—only general specifications are typically available. Still, certain common properties of residential BESSs can already be distinguished. In the majority of cases, the utilized energy storage is a low-voltage (50 V) Li-ion battery, which is associated with relatively high currents. Although the particular topology configurations used in these systems are not revealed by the manufacturers, such voltage level would in general require a rather complex interface converter featuring a transformer for the required voltage step-up. Using RESU10 and RESU10H from LG as a reference, one of the reasons for using a battery with such voltage level is its 14% reduced price, as compared with the higher voltage battery of the same energy capacity. This results in round-trip efficiencies of most residential BESS being around 90%, which seems to be a current technological limit for such configurations.

The current market of BESSs shows a clear trend of their transformation from the auxiliary BESSs, complementing a solar or wind farm with a smoothing energy storage (AC and DC coupling), towards a complete energy system with BES that does not depend on the availability of alternative energy (only AC coupling). While the BESSs of the first type have a DC output and often need a separate grid converter, newer BESSs of the second type are intended for AC operation due to the intrinsic AC interface. From the point of view of their features and functions, the earlier BESSs were focused on local power supply and equalization or shift of peak consumption, but the newer systems have a range of advanced functions, for example, integration on energy system level, i.e., possibility of combining several household grids with BESS into a distributed power plant.

**Table 2.** Summary of BESS for general use and use with renewable energy sources available on the market.

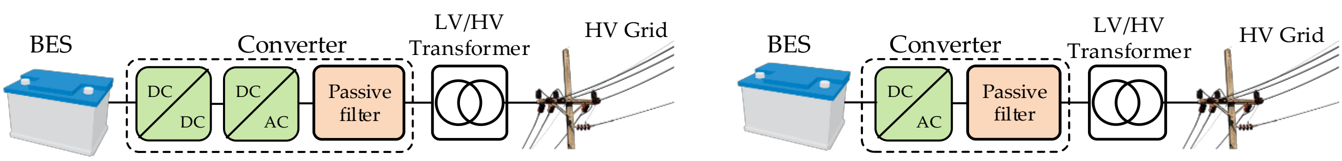
| BESS Manufacturer/Model | Maximal Energy Capacity [kWh] | Charge/Discharge BES Power [kW] | Battery Voltage [V] | Coupling | Reference |
|---|---|---|---|---|---|
| Tesla PowerWall | 13.5 | 5 | 50 | AC | [63] |
| Sonnen Batterie Eco | 15 | 3.3 | 48 | AC | [64] |
| Adara Power (Residential) | 20 | 12 | 50 | AC/DC | [70] |
| Sunverge | Modular up to 19.4 | 6 | 48 | AC/DC | [72] |
| Solax X-ESS G4 or Hybrid X1/X3 + Triple Power (BES) | Stackable up to 23 (4 modules) | 4 | 300 | AC/DC | [74] |
| SolarEdge + RESU10H | 9.8 | 5 | 400 | AC/DC | [75] |
| PowerVault 3 | 20 | 3.3/5.5 | 52 | AC | [76] |
| Puredrive Storage II AC 5 kWh | 5/10 | 3 | 50 | AC | [77] |
| Duracell Energy Bank | 3.3 | 3.3 | 52 | AC | [78] |
| Enphase Encharge 3 | 3.5 | 1.3 | 67 | AC | [79,80] |
| Enphase Encharge 10 | 10.5 | 3.8 | | | |
| Nissan/Eaton xStorage | 4.2 . . . 10 | 3.6 . . . 6 | 90 | AC/DC | [81] |
| Samsung SDI All in One | 3.6 | 4.6 | 60 | AC/DC | [82] |
| Varta Pulse/Pulse Neo 3 | 3.3 | 1.6/1.4 | 50 | AC | [83] |
| Varta Pulse/Pulse Neo 6 | 6.5 | 2.5/2.3 | | | |
| Sunny Boy Storage | External battery | 3.7/5/6 | 360 | AC | [84] |
| Victron Energy EasySolar | External battery | 0.9/1.7/3.5 | 12.8–51.2 | DC | [85] |

### *3.3. Isolated Converters of Commercially Available Residential BESSs*

As it was shown in Sections 3.1 and 3.2, most of the commercially available BESSs utilize a low voltage battery (see Table 2 for details). The use of such a low-voltage battery while maintaining, at the same time, good control performance, requires that the entire BES interface converter or part of it be a low voltage circuit that, in turn, typically means the use of an isolation transformer. The use of the transformer also allows satisfying the potential safety requirements (see Section 2.4 for details). The transformer may be a network transformer operating at the frequency of the supply grid or a high-frequency transformer. Both solutions have benefits and disadvantages briefly considered below.

#### 3.3.1. Converters with Grid-Frequency Isolating Transformers at AC Side

In general, adding of a transformer at the grid side moves the entire semiconductor circuitry into a low voltage operation, but its topology may be almost of any type, as presented below in Section 4. Therefore, there are two large groups of converters with a network transformer: single stage converters (Figure 5a) and converters with two conversion stages (Figure 5b). The BESS may also be equipped with a transformer at the request of the operator and/or legal regulations, in order to meet the operational requirements. This, however, regards more to BESSs for distribution grids, in particular, ABB with the ESSPro product line [86] and NIDEC with the Silcolstart product line [87]. The transformer installed at the AC side makes the operation of the converter possible at lower voltages, but makes the BESS heavier and bulky.

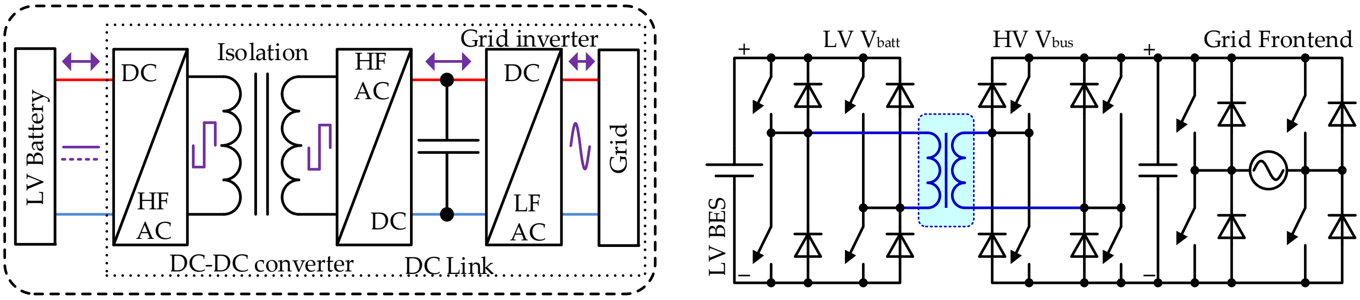



(**a**) (**b**)

**Figure 5.** BESS power electronics converters with a transformer: (**a**) single-stage, (**b**) two-stage.

#### 3.3.2. Converters with High-Frequency Isolating Transformers

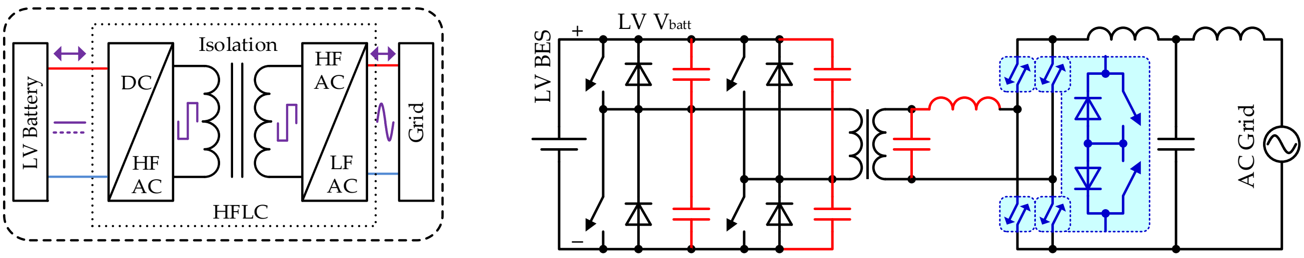
A high-frequency transformer may be allocated in the DC-link (Figure 6a). The most versatile and straightforward kind of the implementation of this approach is the use the circuitry known as dual active bridge (DAB, Figure 6b). Classical DAB [88] is a hard-switching topology that, compared with non-isolated interface converters, considered below in Section 4, is less reliable and energy efficient due to the extra components as well as due to its hard-switching nature. However, if combined with a soft-switching technique, for example, applying a resonant network, it may operate with better efficiency [89,90].




(**a**) (**b**)

**Figure 6.** High-frequency transformers in the DC-link of the interface converter of LV BES: (**a**) functional diagram, (**b**) transformer in conjunction with classical DAB.

In a more advanced approach (Figure 7a), the high-frequency transformer is located at the edge of the DC-link and the AC grid [91]. This requires that the AC part of the topology contains bidirectional switches so that it can operate at both polarities of the grid voltage. The performance of this topology can be improved with the help of resonant networks (red elements in Figure 7b) and advanced modulation methods [92]. Similar topologies and their properties are well described in [93].




(**a**) (**b**)

**Figure 7.** Full-bridge DC-AC converter with a high-frequency transformer: (**a**) functional diagram, (**b**) converter derived from DAB.

The abovementioned DC-DC and DC-AC converters contain an energy-bypassing transformer. Alternatively, the high frequency link may contain also a storage transformer (split coil). In the most explicit form, this storage transformer is seen in a flyback converter. This converter, however, is a DC-DC circuit and its use, therefore, is directly possible only in the DC-link [94] similar to DAB (Figure 6b). At the same time, adopting of the principle to AC networks is possible. For example, the converter presented in [95] contains two flyback converters dedicated to positive and negative half-waves. The inputs of the converters are connected in parallel to a low voltage battery, but their outputs—in series to the grid (Figure 8). The interface converters with a high-frequency storage transformer have the same drawbacks as original flyback converters: rather low power and highly pulsating current on both sides (including battery side) that requires sufficient filtering.

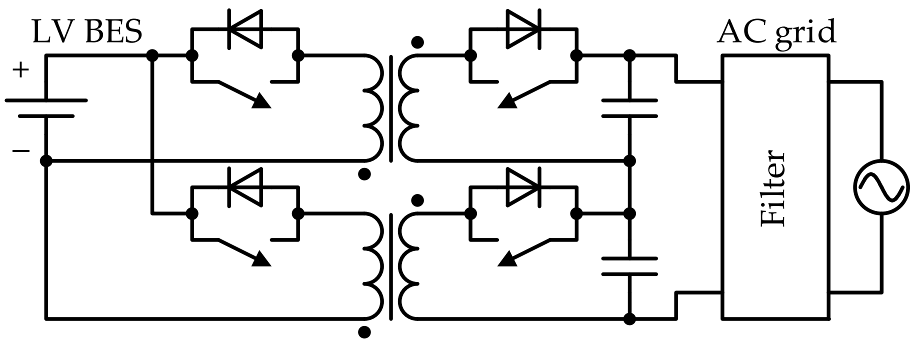



**Figure 8.** Inverter with a high-frequency transformer derived from a flyback converter.

## 4. Topologies of Non-Isolated Interface Converters for High-Voltage Battery Energy Storage Systems

One of the ways to overcome some limitations of the existing residential BESS is to utilize a battery with higher voltage (~200–500 V) and enable the use of a simpler and more efficient interface converter. In fact, some companies, like SolaX, SMA and SunnyBoy, are already on this path. Due to massive electrification of transportation where higher voltage batteries are used to reduce charging current and time, the cost for higher voltage batteries should decline further and make the use of high voltage (HV) batteries more feasible for residential BESSs.

This section is devoted to the analysis of existing and perspective non-isolated power electronic interfaces that can be applicable to the residential HV BESs. The main goal is to highlight the benefits and limitations of various configurations and assess their feasibility and performance. In addition to the standard single-, two-stage and multilevel topologies, emerging configurations like impedance-source, partial and fractional power converters are analyzed.

### *4.1. Functions and Structure of Interface Converters for BES*

According to the analysis of commercially available residential BESSs, two main configurations can be distinguished: DC- and AC-coupled. The first group is generally represented by the power electronic systems that are often referred to as "hybrid inverters" (Figure 9a). They allow integration of both PV and battery into a single multiport unit. Such solutions are well-suited for new installations, but the choice of suitable storage configurations could be limited. On the other hand, the AC-coupled storages are often stand-alone systems that are directly connected to the residential AC grid (Figure 9b). In general, such solutions are more flexible, as they can be integrated into any existing installation. However, for such systems, charging of a battery from a PV typically involves more energy conversion stages, with a negative impact on efficiency.

The interface converter of a BES needs to perform two main functions, along with a range of auxiliary application-based functions. The main functions of the BES are sinusoidal shaping of the AC grid current and forming the DC current of the BES in both directions of power flow. The abovementioned functions can be implemented in a single stage bidirectional DC-AC inverter/rectifier; however, such solutions are typically overall less efficient due to battery voltage variation as compared to two-stage systems [96]. Therefore, the BES interface is usually comprised of a bidirectional DC-DC stage that is interfaced with a battery, followed by the DC-AC inverter/rectifier. The state-of-the-art and other potential configurations of power electronic interfaces for HV BES are analyzed in the following sections.

### *4.2. Single Stage DC-AC Bidirectional Inverters/Rectifiers*

This section presents the state-of-the-art and emerging single-stage grid-tie inverter/rectifier topologies. The main goal of these systems is to convert a DC voltage into the sinusoidal AC waveform and vice versa. Most commercial systems require the

DC voltage to be relatively stable, with their value higher than the amplitude of the grid voltage, while some of the emerging topologies potentially offer enhanced flexibility.

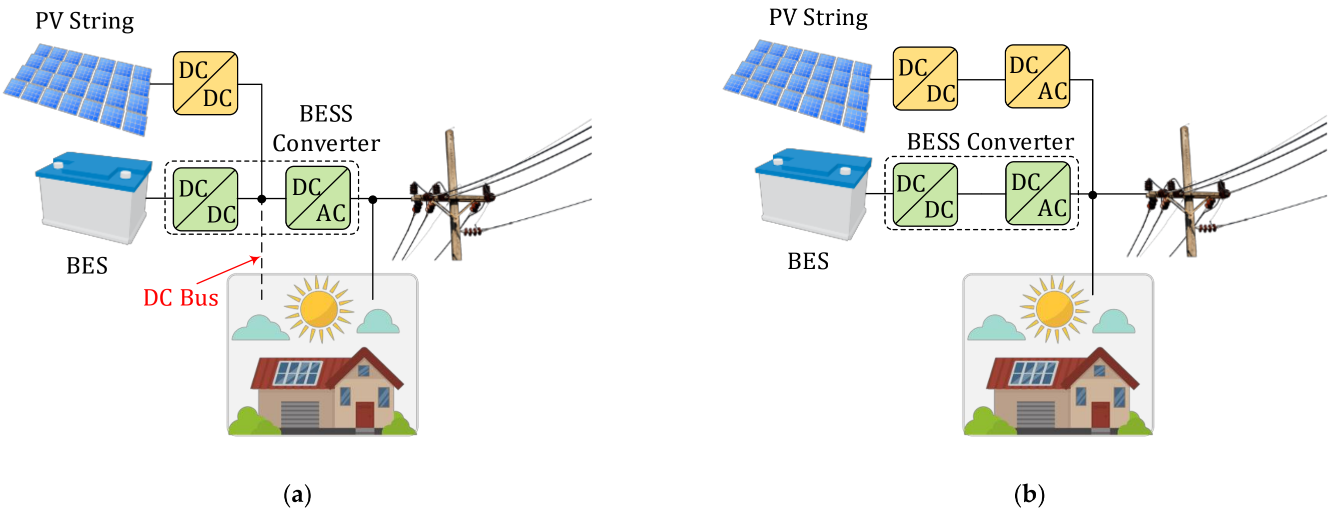



**Figure 9.** Coupling of units in residential energy systems: (**a**) DC coupling, (**b**) AC coupling.

4.2.1. Bridge Converters

A high voltage battery can be attached to the grid through a single stage bidirectional (four-quadrant) interface converter. The most frequently mentioned converter is a transistor bridge. Such bridge itself is a parallel connection of two (three) transistor legs with two transistors (and anti-parallel diodes) in each (Figure 10). The converter includes also an inductance coil between its AC terminals and the grid implementing an AC current source (Figure 10a). A diagonal couple of transistors and the couple of diodes located in the opposite diagonal form a chopper capable of converting the grid voltage at its particular polarity. In Figure 10a, red elements represent the chopper for the positive half-wave, but blue elements—for the negative. The chopper is bidirectional and can be considered as a buck converter supplied from the DC bus or as a boost converter supplied from the AC grid [97]. One transistor leg can be substituted by a series connected capacitors (capacitor leg), thus forming a transistor-capacitor bridge (Figure 10b), more frequently named "half-bridge" [97]. In this topology, it is also possible to identify two choppers for both half-waves of AC voltage. Finally, it is possible to apply this approach of schematic synthesis to three phase systems (Figure 10c,d). This forms the three-phase transistor bridge and the three-phase transistor bridge with a capacitor leg coupled to the grid via inductor-based AC current source [98].

4.2.2. Topologies without Explicit Bridge

The intrinsic choppers shown in Figure 10 can be deployed without forming an explicit bridge. This scheme is defined as a dual-buck grid converter known since 1997 [99,100]. With this approach, the elements of the "positive" and "negative" choppers are different, which enables them to be further optimized.

Figure 11 shows how the elements of implicit choppers are extracted (red elements—for positive and blue elements—for negative). With this approach, the inductance coil is not shared between "positive" and "negative" branches (Figure 11a). These coils can be magnetically coupled (Figure 11b), providing their lower weight/volume and therefore, lower weight/volume of the converter itself [101], without the reduction of the performance and reliability of the converter. Alternatively, both branches can be combined through a couple of series connected diodes (Figure 11c) [102], keeping the same advantages.

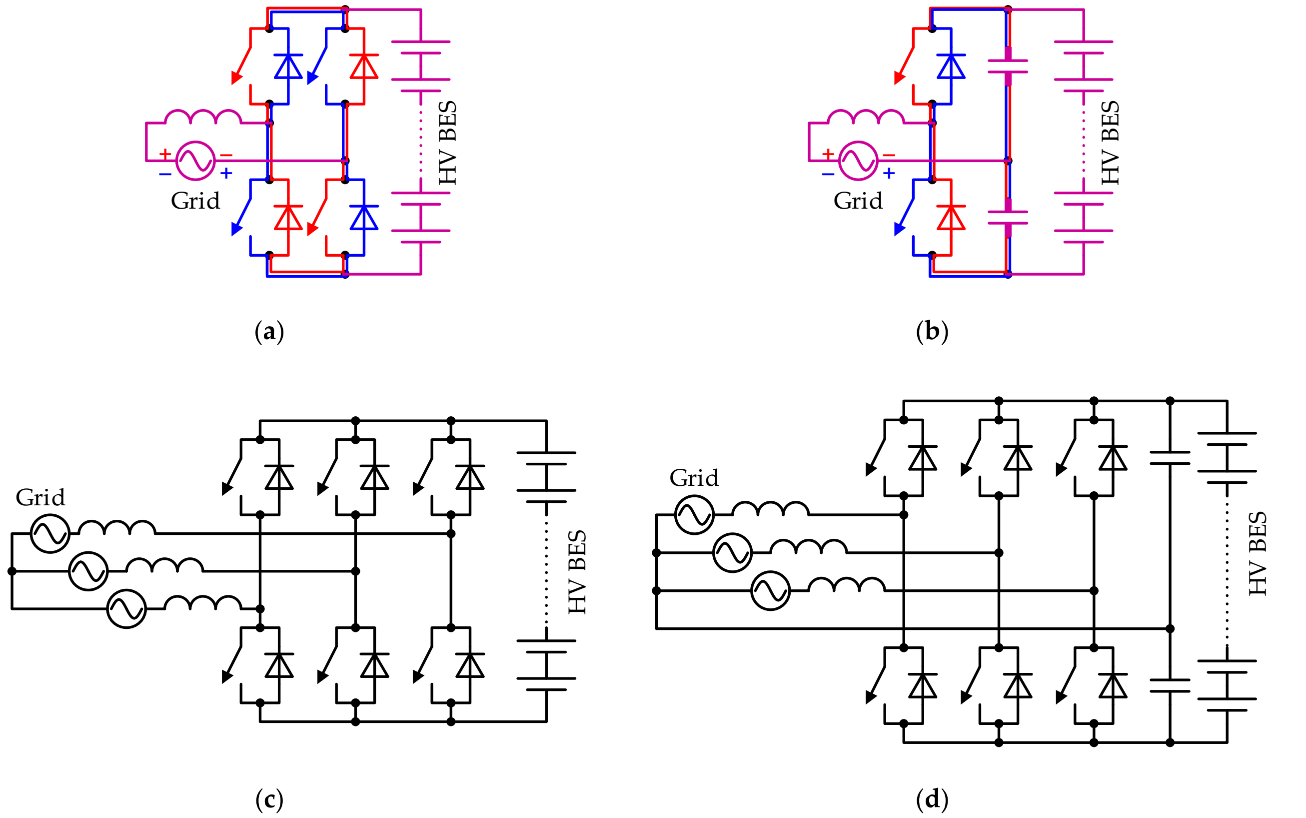



**Figure 10.** Configurations of single-stage bridge rectifiers-inverters for BESs: (**a**) AC current sourced transistor bridge, (**b**) AC current sourced transistor/capacitor bridge (half-bridge), (**c**,**d**) three-phase schemes.

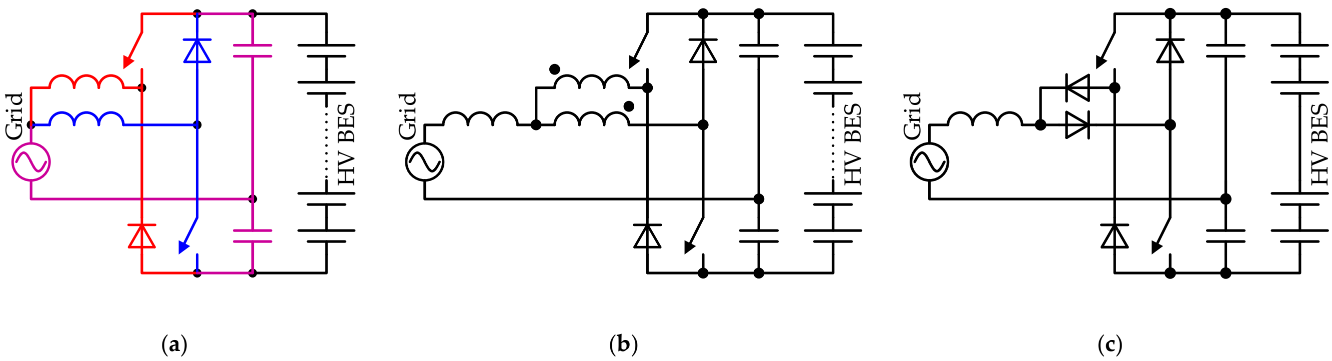
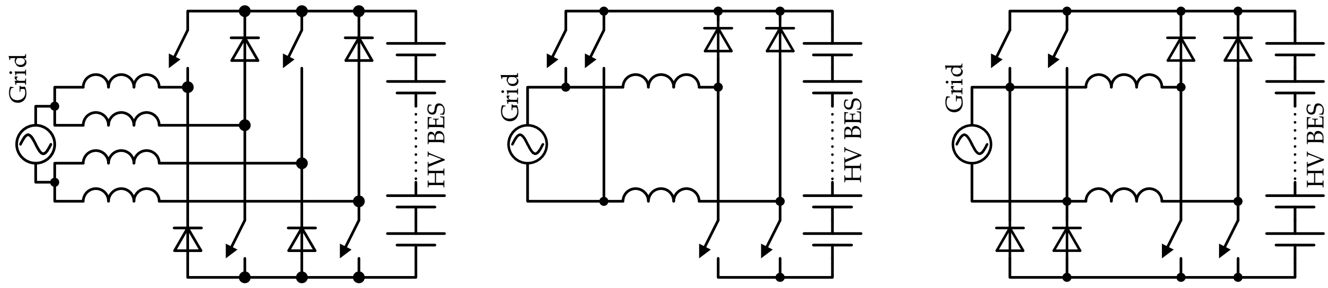



**Figure 11.** Dual-buck grid converter: (**a**) derived from half-bridge, (**b**) magnetically coupled branches, (**c**) diode coupled.

Extracting of the intrinsic voltage converters at both grid terminals of a full-bridge converter forms another kind of the dual-buck grid converter (Figure 12a) [102]. Another version derived from the full-bridge topology can be synthesized by means of direct combining of two DC sourced buck converters—attached to each terminal of the grid [76]. In this converter, the switches located at the grid side are continuously conducting at the corresponding grid voltage polarity that reduces switching losses. Additionally, such converter may be "tied to positive voltage node" (as shown in Figure 12b) or "ground tied". Finally, adding two diodes at the grid side (Figure 12c) allows operating in "ground tied" and "positive node tied" modes [103,104], making the operation of the switches more symmetrical. The converter shown in Figure 12b can be equipped with magnetically coupled inductance coils or coupling diodes, as shown in Figure 11.




(**a**) (**b**) (**c**)

**Figure 12.** Dual-buck grid converters: (**a**) derived from full-bridge, (**b**,**c**) synthesized of two combined buck converters.

Due to a low number of elements, the considered single-stage converters operate with best efficiency at their particular operation point. However, when considered in conjunction with the attached battery, their efficiency is not outstanding and drops significantly at other operation points due to the higher losses in the converter and the battery [86]. In addition, these converters operate as an AC grid supplied boost or a BES supplied buck converter that requires minimal battery voltage to be higher than the amplitude of the grid voltage.

### 4.2.3. Multilevel Converters

Multilevel converters (MLC) can be considered as a specific kind of the single-stage converters, processing energy in separate cells of a BESS battery. In contrast to the above-considered topologies that always deal with the same DC voltage or with the entire battery, the multilevel converters form their output of DC voltage that may have several levels obtained directly from the battery. The advantages of multilevel converters are lower harmonic distortion, switching losses and electromagnetic interference [105]. There are three main topologies of multilevel converters: cascaded H-bridge converters (also known as multilevel converters with independent sources), neutral point clamped multilevel converters (also known as diode clamped multilevel converters), and multilevel converters with flying capacitors.

#### Cascaded H-Bridge Converter Structures

In the case of cascaded H-bridge multilevel converters, each phase contains several series-connected modules (Figure 13a) composed of dedicated cells and an inverter, together forming an independent source. Within a BESS [106], these sources can be charged and discharged more evenly due to the independent nature of their involvement in the current path and potentially free exchange of the sources [107].

There exist various types of power converters and energy storage building blocks. The most common converter is a single-phase transistor bridge (H-bridges) shown in Figure 14a, which generates AC voltage on its output, thus controlling the charge or discharge process of the connected battery cells. Another typical configuration given in Figure 14b includes an AC generating H-bridge in conjunction with a synchronous buck converter that compensates voltage changes in the cell(s).

Lastly, a successful commercial implementation of BESS with a multilevel converter was offered by SolarEdge [108]. It is based on a multilevel DC converter with multiple DC modules connected in series (Figure 13b). Allocation of the multilevel structure in the DC bus enables significant simplification of the cell converters (Figure 14c). The DC/DC converters can operate in the following modes: balancing circuit, charger and battery discharger. In turn, if the DC bus is formed by an MLC, the grid frontend can be a simple commutation matrix or an efficient pulse mode inverter or a short-circuit proof converter with an impedance network. A similar topology developed by ABB for distribution networks [109] includes an array of complex cells containing two transistors and a battery with switches and capacitors. A cell may work as a boost or buck converter and is capable of shunting the cell if needed.

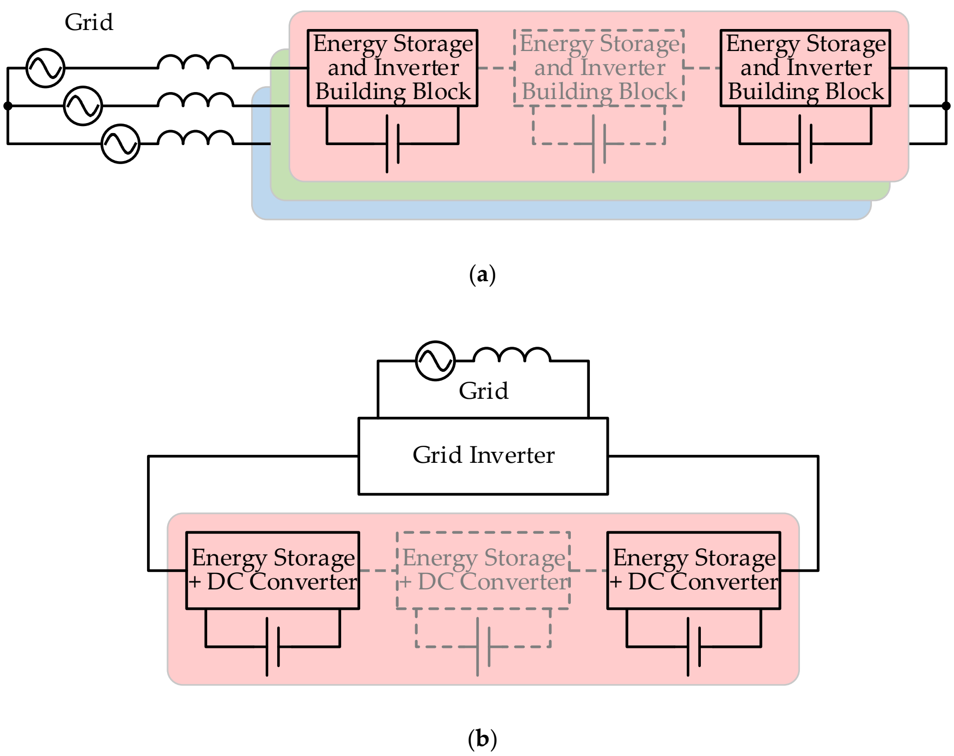



**Figure 13.** Functional diagrams of cascaded H-Bridge multilevel converters: (**a**) traditional configuration of AC MLC, (**b**) configuration DC MLC with unipolar cell converters and grid frontend.

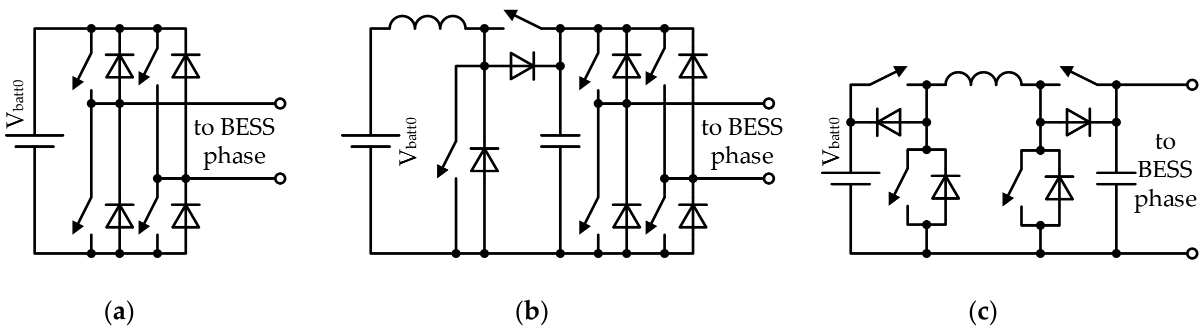



**Figure 14.** Power converters for multilevel converter building blocks: (**a**) full bridge or H-bridge, (**b**) H-bridge with correcting synchronous buck converter, (**c**) unipolar bidirectional converter [108].

Neutral Point Clamped Multilevel Converters

The simplest kind of the neutral point clamped multilevel converters is known as the diode clamped topology (Figure 15a). It has quite high efficiency compared to other topologies. However, there are some disadvantages: the number of power diodes is quadratic related to the level count, which makes this topology quite difficult to use when a large number of levels is needed. Another disadvantage of the topology is that charge balancing in the capacitors is needed. Another type of the neutral point clamped multilevel converter is an active clamped multilevel converter shown in Figure 15b. Additional switches enable the distribution of power losses more evenly between the switches. Besides, it is possible to synthesize 0 V level differently, providing different charge/discharge paths.

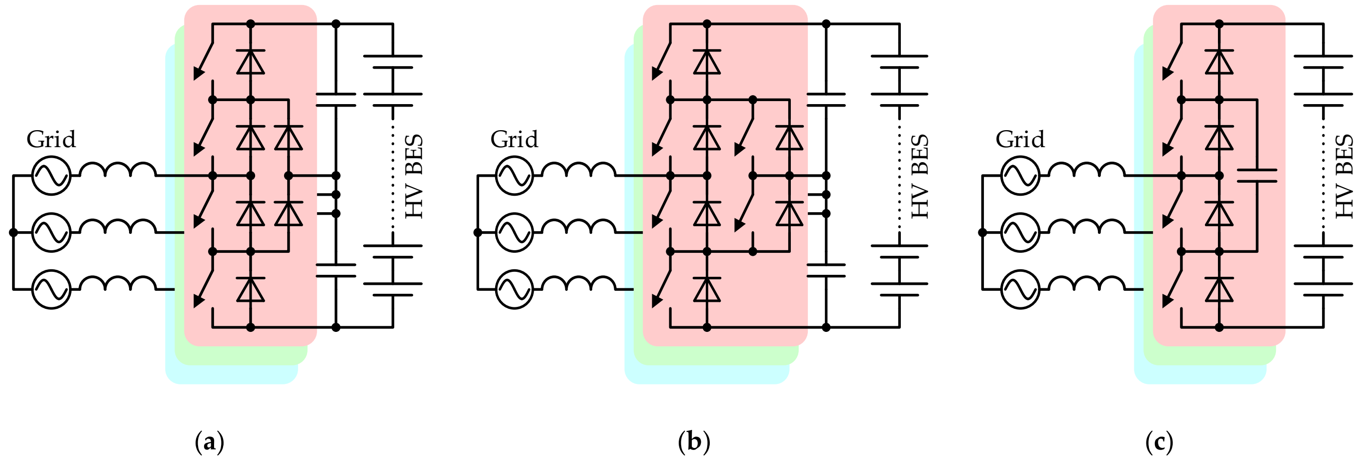



**Figure 15.** Multilevel converters with solid HV battery: (**a**) diode clamped, (**b**) active clamped, (**c**) flying capacitor.

The use of neutral point clamped converters in the BESS system is described in [110,111]. Reference [112] demonstrates the use of neutral point clamped and active neutral point clamped converters in BESSs. In [113], an overview of modular converters (including active neutral point clamped converters) in BESS systems is given. Diode clamped and independent source multilevel converters in BESS applications, indicating also larger operating range of the diode clamped converters, are compared in [114].

Multilevel Inverter with Flying Capacitors

The main difference between multilevel converters with neutral point clamped and multilevel converters with flying capacitors (Figure 15c) is that instead of clamping diodes, capacitors are used. Similar to the diode-clamped topology, the main disadvantage of the multilevel inverter with flying capacitors is the large number of used capacitors, which makes the practical implementation of this solution larger in terms of packaging. In spite of this drawback, some recent papers report that the topology itself can be successfully applied in BESS based on GaN switches: [115] presents a BESS with a 13-level converter, but [116]—a 9-level converter for aircraft. In addition, the BESS interface converter offered by SolarEdge in [108] utilizes the MLC with flying capacitors as a grid inverter.

### *4.3. Impedance-Source Bidirectional Inverters/Rectifiers*

The problems of conventional topologies related to the battery voltage variation can be mitigated with the family of impedance source (IS) converters. These topologies incorporate a special network, which allows step-up of the input voltage using a shoot-through state in the inverter bridge, which is a prohibited condition in conventional inverters. As a result, IS converters can be less prone to short-circuit faults. There is a variety of impedance source networks proposed in the literature for a range of applications with different properties and features (Figure 16), including three-phase and multilevel configurations [117]. The majority of basic impedance source topologies were initially unidirectional; however, some studies address the bidirectional versions potentially suitable for residential BES [118,119].

### *4.4. Bidirectional Two-Stage DC-AC Converters*

This section presents the state-of-the-art and emerging power electronic interfaces for BES, featuring two explicit stages. In a general case, the first stage is a bidirectional DC-DC converter, which processes varying battery voltage and controls the charge/discharge current. It operates in conjunction with the DC-AC inverter/rectifier addressed in the previous section, which provides interface with the grid.

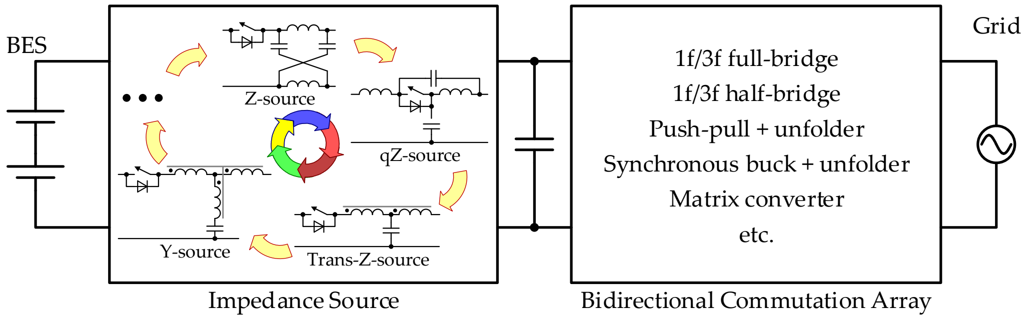



**Figure 16.** Generalized configuration of the BES interface converter with an impedance source.

In the most obvious operation mode, this DC-DC converter provides the stabilized voltage in the DC-link at all operation points of the battery (Figure 17a) while the rectifier-inverter modulates the voltage at the grid end according to the phase of the network voltage and required grid current. It was demonstrated that two-stage configurations are overall superior to the single DC-AC inverter/rectifier in terms of efficiency throughout the battery voltage range [86]. Moreover, the stable DC-link voltage allows integration of other DC sources and loads; therefore, such solutions can be suited for both DC- and AC-coupled BESS.

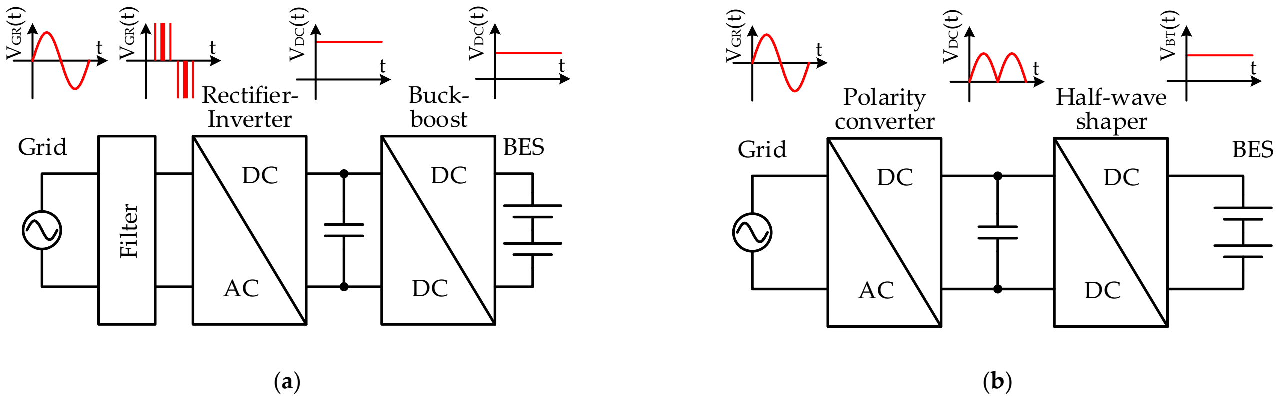



**Figure 17.** Operation and configuration of BES interface converters with two stages: (**a**) common DC-link, (**b**) unfolding topology.

However, one more operation mode and configuration is possible. In this mode, the DC-DC converter forms unipolar sine half-waves in the DC-link, but the rectifier-inverter applies the formed half-waves to the grid with the correct polarity (Figure 17b). In the second case, the rectifier-inverter does not operate in a real switch-mode—it just commutates the half-waves at the grid frequency. Therefore, in this operation mode, the switching losses of the rectifier-inverter are negligible, while the grid filter can be omitted or reduced due to the continuous profile of the voltage at the grid port of the rectifier-inverter [120]. In the single-phase configuration, the AC-DC converter is a bridge or half-bridge circuit, close to that shown in Figure 16 without the inductance coil. Depending on the required power and input connection, it can be a single-phase [120–122] or a three-phase [122,123] circuit.

#### 4.4.1. Two-Stage Converters with Stabilized DC-Link

The typical configuration of a two-stage converter assumes voltage stabilization at an intermediate DC-link to compensate battery voltage variation and provide optimal operating conditions for the DC-AC inverter/rectifier. Such configuration can be suited for both DC- and AC-coupled BES. The standard DC-DC stage topologies include buck, boost, buck-boost, etc. The common disadvantage of these standard configurations is that both stages have to be rated for the full power of the system. This results in increased cost and negative impact on the efficiency. One of the recent trends in the power electronic studies is the use of advanced topologies of the DC-DC stage like differential, partial and fractional power converters that allow operation with lower voltages/currents and minimization of power losses. The use of these topologies in BES interface is considered below.

Standard Topologies of DC-DC Converters

The choice of the secondary (DC-DC) converter or the converter at the battery end depends on several factors. First of the all, this converter has to be bidirectional. Besides, this reduction of the losses requires that the number of switches is minimal, which enables only simple choppers. Finally, the configuration/mode of the two-stage interface converter (stabilizing or unfolding) as well as the voltage of the battery are important. Below, the latter issue is addressed in detail.

In the case of the two-stage converter with a stabilized DC-link, its grid unit may operate correctly if the voltage of the DC-link is higher than the amplitude of the grid voltage. On the other hand, keeping this voltage level on the battery is not reasonable because it would reduce the advantages of the two-stage configuration. Taking into account the realistic voltage gains of the circuits with the boost function of 2–3 and voltage difference of the fully discharged and fully charged Li-Ion batteries of 60–100%, the voltage of the fully charged battery could be at least twice lower than the amplitude of the grid voltage or about 200 V. In the given paper, this level is considered as a medium level, but such batteries abbreviated as MV BES. The case of the unfolding configuration/mode additionally requires that the DC-DC chopper is capable of converting the BES voltage down to zero level. Together, as a result, the following buck-boost converters are suitable for both configurations/modes: classical (Figure 18a) and non-inverting (Figure 18b) bidirectional buck-boost converter, Zeta-SEPIC circuitry that is linked through its primary inductor to the battery or the grid (Figure 18c), as well as the bidirectional Čuk converter (Figure 18d). In addition, a synchronous buck converter (Figure 18) is applicable in the case of the stabilizing configuration/mode only.

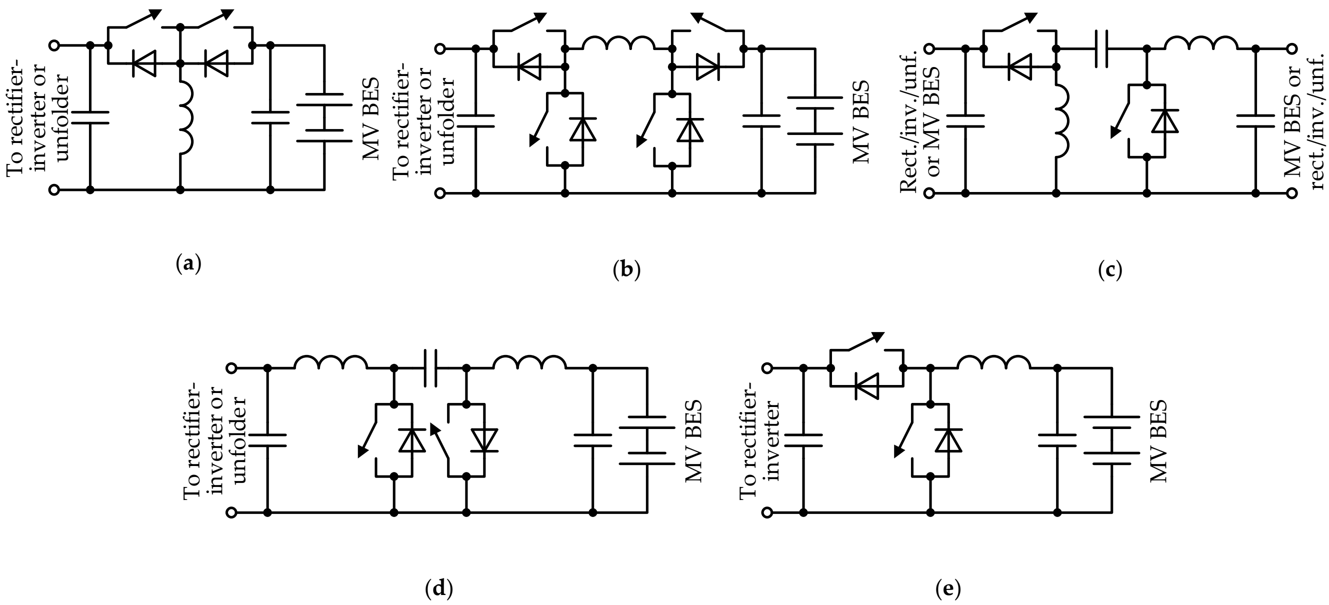



**Figure 18.** DC-DC stage of BES interface converters with two stages: (**a**) inverting bidirectional buck-boost, (**b**) bidirectional non-inverting buck-boost, (**c**) bidirectional zeta-SEPIC, (**d**) bidirectional Čuk, (**e**) synchronous buck.

Zeta-SEPIC-Čuk topologies, however, are usually not considered as powerful converters, which disables them for applications like BESS. On the other hand, the remaining (non)inverting buck-boost and synchronous buck topologies can be equipped with additional elements for reducing losses, smoothing current ripple and better control performance (more accurate regulation for the same range of duty cycle): add-on circuits for zero-current/resonant switching, tapped (coupled) inductors or qZ links [120].

Differential Power Converters

Differential power converters (DPCs) are a kind of partial power processor (PPP). In turn, PPPs are a quite recent group of converters that are typically used in conjunction with renewable energy sources and storages. As it follows from their title, the main feature refers to dealing only with a part of the total system power. PPPs can be systematized in a number of ways, such as considering their topology or application. However, most commonly, PPPs can be divided into different groups [124] according to their power flow. From this point of view, three groups could be differentiated: differential power converters that internally link elements of the systems, partial power converters connecting system input and output, fractional power converters dealing with a fraction of entire set of power sources/storages, as well as mixed topologies. Finally, it must be noted that the difference between differential, partial and fractional power converters is sometimes quite fuzzy. For example, in [125,126], identical topologies are entitled as partial and differential. In a similar way, most of the topologies considered in [127] as partial power converters, in fact, operate as fractional power converters.

DPCs are mainly used in various balancing systems [128,129]. There are two types of such converters. The first one transfers the energy between two typically adjacent elements and is known as element-to-element (E2E) converter; alternatively, in another option, the energy circulates through a common bus (B2E). The DPC normally operates with batteries, but according to some reports, this converter technology is applied to photovoltaics [128].

The E2E architecture is used in systems with the same type of cells, for example, for balancing batteries (Figure 19a). The main advantage of this architecture is that each converter operates at significantly lower voltage and current values than the entire system. The disadvantages of this architecture are the interconnectedness of the converters and the impossibility of their operation separately.

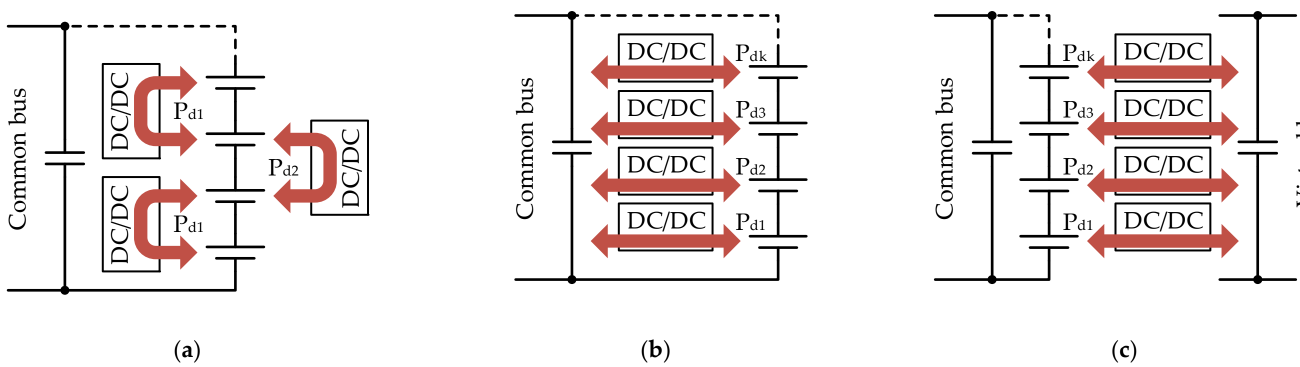



**Figure 19.** Differential power converters: (**a**) Element-to-Element, (**b**) Element-to-common-bus, (**c**) Element-to-virtual-bus.

The B2E architecture works with a common bus connected to the output (Figure 19b) or with the independent "virtual" bus dedicated to the energy transfer (Figure 19c). Each element is connected to the bus via own converter. Compared to the E2E architecture, this approach is more flexible, but neighboring cells are independent of each other. However, an isolating converter suitable for the full bus voltage is required.

All kinds of DPCs fit well the cell balancing function needed also in BESSs. At the same time, the use of B2E DPCs as BES and grid interface converters is complicated due to the following: (1) DC output requires an inverter or unfolder and (2) because the total power of converters, in fact, is not reduced, but just split into several parts. Lastly, the E2E DPCs are not applicable as BES and grid interface converters due to the absence of the common link.

Partial Power Converters

Another group of PPP links the input and the output of the system. While one part of the energy from the source to the load goes directly, the converter transfers only the necessary reminder. As can be seen from Figure 20, in the classical converter type (Figure 20a), all the output power passes through the converter, which leads to a higher efficiency and significant losses. In the case of a PPC, a significant part of the total energy enters the load without conversion and does not produce losses. Only the energy going through the converter, adjusted by the converter to control the energy flow, produces losses (Figure 20b). Thus, compared to a classic converter, PPCs have potentially better efficiency and smaller dimensions for the same power. The PPCs may operate with reduced voltage (Figure 20c), current or both.

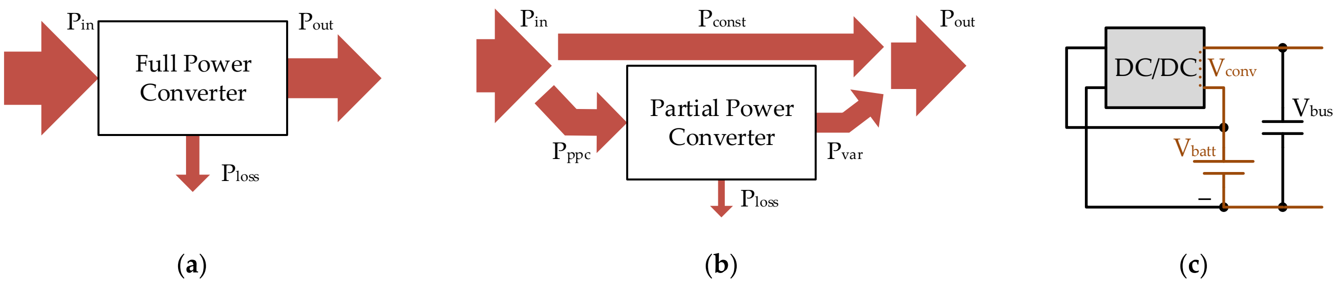



**Figure 20.** Full power operation vs. partial power operation: (**a**) power distribution in full power converter, (**b**) power distribution in partial power converter, (**c**) diagram showing operation with reduced voltage.

It is possible to distinguish two groups of PPCs: with an isolated and with a non-isolated converter. The isolated converter can be applied in a quite free form. That is why such PPCs can be of two types: parallel input—serial output, as well as serial input—parallel output (Figure 21). In the first case (Figure 21a), the input source and the input of the converter are connected in parallel, while the output of the converter and the input source are connected in series (S-PPC). The configuration is suitable to increase the voltage. In respect to the battery, the parallel input converters can be considered as partial current converters because only part of their battery current is transferred to the output (bus) through the converter. On the other hand, in respect to the output, operation occurs with reduced voltage because only part of output voltage is applied to the converter (see also Figure 20c).

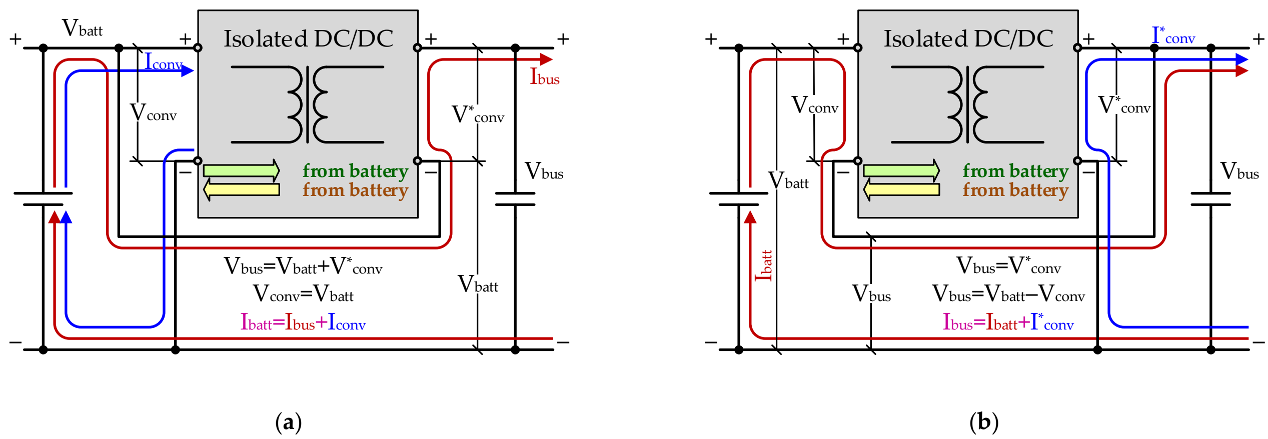


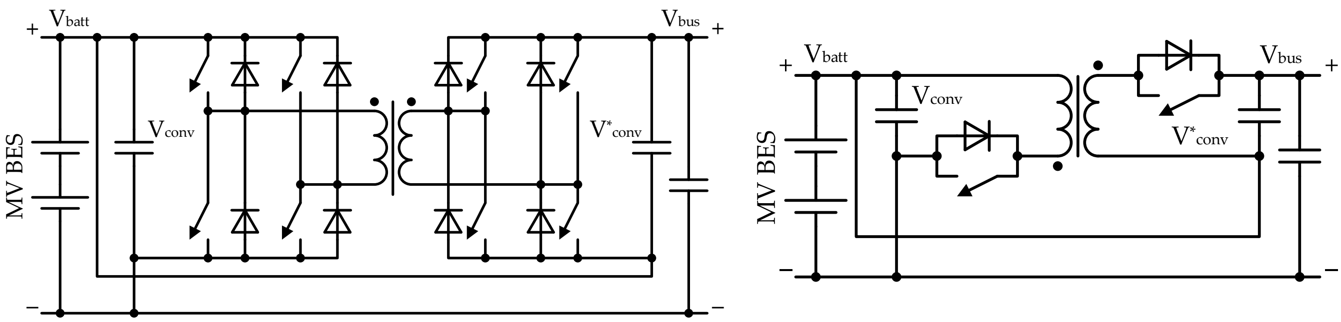

**Figure 21.** Structures of partial power converters: (**a**) parallel input—series output, (**b**) parallel output—series input.

In the second case (Figure 21b), the input source is connected in series with the input of the converter, but its output and the source are connected in parallel (P-PPC). The configuration is suitable to obtain higher output current. In respect to the battery, the series input converters can be considered as partial voltage converters because only part of their battery voltage is converted and passed to the output.

It is obvious that both topologies are symmetrical and counter-reversible. In respect to the output (bus), the first configuration is a partial voltage converter, but the second one—a partial current converter. To some extent, these PPCs are similar to an autotransformer and can be described by similar mathematical expressions extracted from Kirchhoff's voltage and current laws.

The PPC topology provides benefits when the difference between the input and the output voltage is relatively small and only a small amount of energy is being converted by PPC. Due to a more complex design and a larger number of active elements, the larger difference between the input and the output voltages produces lower efficiency. Moreover, at 100% of the difference, the efficiency will be less than that of a classical converter.

Practical PPC implementation depends on the particular application. Normally, reports consider PPC with a DAB converter at each end of an isolating transformer that produces a fully bidirectional PPC (Figure 22a). In many applications, the bidirectionality can be omitted, but PPC—reasonably simplified. For example, in [130,131], which address PV systems, the simplification finally produces full-bridge + buck configuration, in [131,132]—full-bridge + push-pull, but in [130,132]—a kind of classical flyback. The latest converter can be easily turned to a bidirectional one (Figure 22b).




(a) (b)

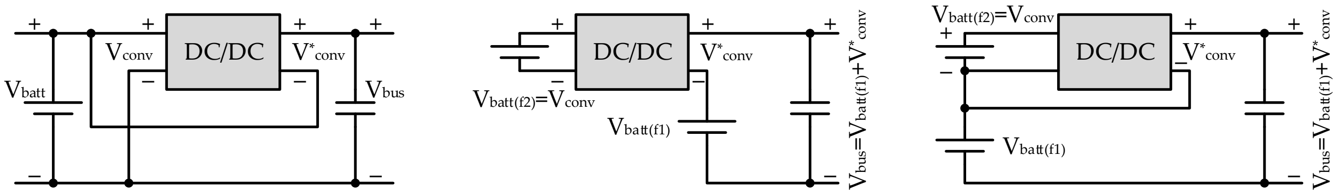
**Figure 22.** Examples of PPCs: (**a**) parallel input—series output PPC with DAB, (**b**) parallel input—series output PPC with flyback converter.

A PPC topology with a non-isolating converter could be potentially simpler, contain fewer components, and have higher efficiency. Attempts have been made to implement such non-isolating schemes. For example, refs. [133–135] report the voltage buck-boost topology based implementation applied for battery or bus voltage magnification. It is pointed out that the extra feedback capacitor installed in these schematics is required for direct power feedforwarding. However, it is possible to show that the obtained converters are, in fact, ordinary boost or buck converters—see [136] for details.

Fractional Power Converters

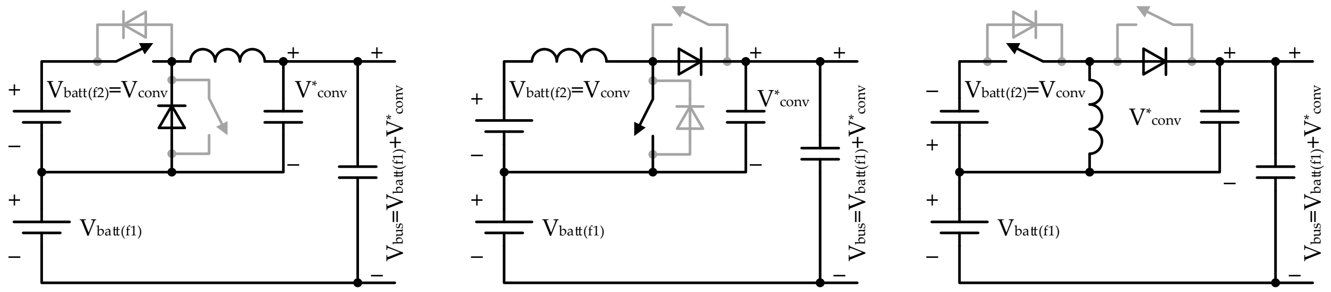
Fractional Power Converters (FPCs) deal with an explicit part of the entire power supply, for example, with several cells of BES [137,138]. In contrast to PPCs, where the reduced operating voltage of the converter is obtained as a difference on the entire input/output, FPCs process already reduced voltage—a section of the entire power supply (similar consideration could be applied to current conversion).

The fractional power processing may utilize an isolated (Figure 23b) or a non-isolated (Figure 23c) scheme. Successful examples of non-isolated converter use have been demonstrated in conjunction with a battery of PEVs [137] or grid BESS [138]. The mentioned reports explore several DC-DC choppers functioning as FPC (Figure 24 shows discharging configurations in black, but charging—in gray). In this case, the non-isolated converter obviously deals with reduced voltage, thus providing true partial power processing. On the other hand, the fraction of the power supply associated with the converter operates differently from the rest of BES. It has different average charge/discharge current. Moreover, depending on the applied chopper, it may conduct pulse-mode current. This may lead to shorter operation cycles, limited state of charge and, finally, may lead to a worse state of health for the "processed" cells.




(**a**) (**b**) (**c**)

**Figure 23.** Partial power converters (**a**) vs. fractional power converters: (**b**) isolated, (**c**) non-isolated.

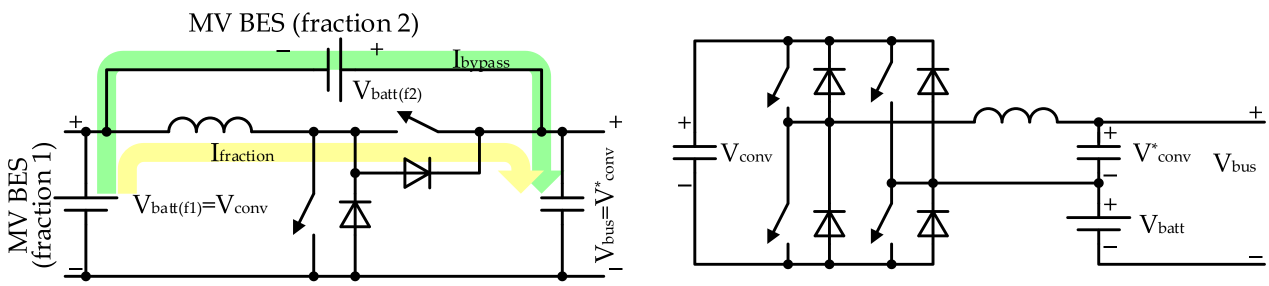



(**a**) (**b**) (**c**)

**Figure 24.** Examples of non-isolated fractional power converters (in discharge mode): (**a**) buck, (**b**) boost, (**c**) buck-boost.

The FPC shown in Figure 24c is also quite impractical because the polarities of the input/output voltage are different, which splits the battery or narrows the regulation range. On the other hand, the use of non-inverting buck-boost topology would double the static and dynamic losses of the switches.

Finally, the considerations on the non-isolated PPC with a feedback capacitor (given in the previous section) may also produce, in fact, an FPC if the feedback capacitor is substituted with an energy source or storage (battery, supercapacitor, PV cells etc.) capable of keeping its voltage at a constant level. Then the part of the current is actually bypassed, but the other—processed in the converter (Figure 25a). Practical importance of this converter is questionable because one fraction of the battery is loaded with increased current and charged/discharged more intensively.




(**a**) (**b**)

**Figure 25.** Specific kinds of FPC: (**a**) FPC synthesized from "non-isolated" synchronous buck PPC, (**b**) fractional power conversion with "virtual fraction" [139].

Another example of the implementation of non-isolated partial power conversion is given in [139]. This example, however, may also be considered as a fractional power converter with "virtual" fraction formed of a DAB and an ordinary capacitor. Here, the DAB processes low voltage of the capacitor while the battery is attached in series without processing (Figure 25b). Although, in [139], with the focus on the DC-AC systems, partial conversion of power occurs in the DC-link. Due to the limited energy capacity, the configuration is suitable for compensation of regular short term voltage fluctuation or current compensation that happens, for example, within the cycle of the supply grid (20 ms).

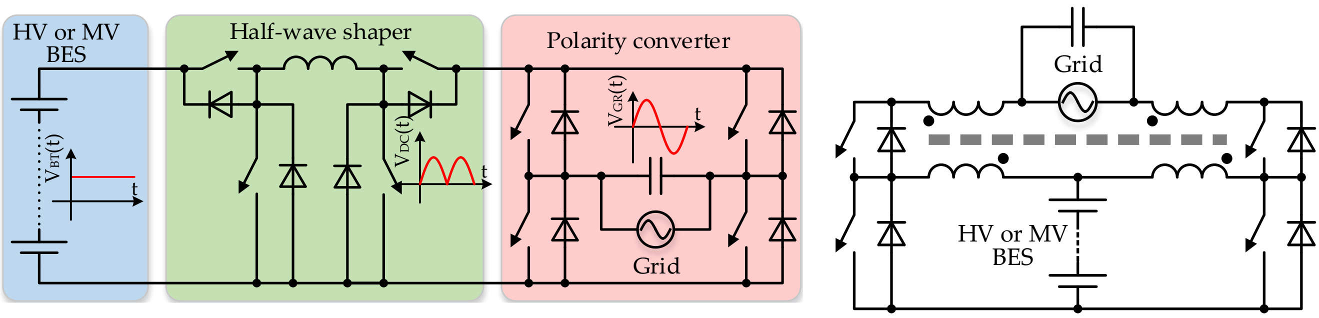
#### 4.4.2. Two-Stage Converters with Pulsating DC-Link

In order to reduce the overall switching losses of the two-stage system, a configuration with inverting unfolder can be used. In this case, the DC-DC converter forms unipolar sine half-waves in the pulsating DC-link, but the interface inverter applies it to the grid with the proper polarity.

The Li-ion battery can handle the current ripple without significant effect on their lifetime, thus the use of pulsating current can be justified [140,141].

##### 1-ph Unfolders

As it was stated previously, an unfolding circuit provides grid-frequency commutation of the unipolar voltage formed by a high-frequency switch mode DC-DC converter to provide sinewave matching to the grid polarity. Paper [142] proposes a combination of a buck/boost non-inverting converter and an unfolding H-bridge (Figure 26a). This configuration directly corresponds to Figure 17b and can be considered as a standard double stage converter with a pulsating DC-link. In [143], the operation and the experimental verification of a buck-boost inverter/converter based on tapped inductor are addressed. The inductor magnetically couples four windings with equal turn-ratio (Figure 26b). In the converter presented in [143], in contrast to [142], explicit parts cannot be identified.




(**a**) (**b**)

**Figure 26.** Examples of single-phase unfolders: (**a**) buck-boost converter with unfolding H-bridge, (**b**) tapped inductor buck-boost converter.

##### 3-ph Unfolders

Three-phase converters with low frequency unfolding stage utilize principles similar to those of single-phase unfolders. However, the presence of three phases requires that at least two voltages/currents be formed actively by the dedicated voltage/current source (shaper), but the third one is obtained as a sum/difference of the other two. Within a period of the grid, the principles how the actively shaped voltages/currents are applied to the grid change six times (Figure 27a,b).

Working principles of unfolder topologies are provided in [144]; however, the converters described there are unidirectional and do not fit the requirements of bidirectional operation. An example of such converter from [144] is a topology derived from a three-phase two-level voltage source inverter. In this case, amplitude modulated high-frequency output of a phase modulated high-frequency inverter (H-bridge was taken as an example) is rectified and filtered. Then the output of a filter is unfolded by a three-phase inverter, thus forming three-phase alternating current. For the bidirectional operation, one or multiple DC-DC converters should be used as current sources. For example, refs. [145,146] show a three-phase inverter, where two DC-DC converters were taken as current sources and are connected in parallel to the BES. DC-DC converter outputs are connected in series, thus forming three voltage levels—high, low and neutral. Then the modulated voltage waveforms are unfolded by a three-level inverter, which is derived from a diode clamped multilevel converter [146] or Vienna rectifier [145] (Figure 27c). The study in [147] provides experimental verification of the topology in [146].

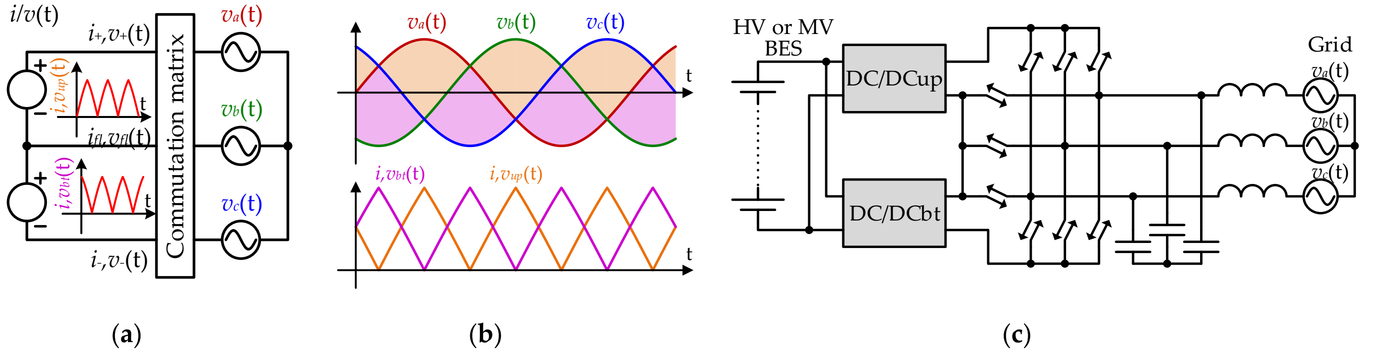



**Figure 27.** Three-phase unfolders: (**a**) general principle, (**b**) operation diagram, (**c**) example of implementation.

## 5. Generalizations and Discussion

One of the main trends in the area of residential BESSs is a shift from stand-alone systems for a particular task, like the increasing local renewable energy self-consumption using basic algorithms, to a complex integrated system, aiming to achieve multiple different goals. Some commercial BESSs can provide a supply during a power cut, effectively acting as uninterruptable power supplies. The use of advanced energy management algorithms enables smart scheduling and energy trading, further improving the functionality of these systems. The integration on a system level allows provision of ancillary grid services and enables forming of a microgrid with extended levels of flexibility. Nevertheless, currently there are still a number of technological and legal barriers that limit a ubiquitous application of the residential BESS. However, the new regulations, subsidies and initiatives offered and developed by governmental structures in many countries are aimed to stimulate the installation of these systems and make full use of their potential [148].

Our review of the commercially available BESS and the corresponding intellectual property right items shows that despite a whole range of available solutions, the market of residential BESSs is still advancing. Presently, it is strongly influenced by a forecasted price reduction of the Li-ion battery cells and further improvements in the battery chemistry. Technical information about available products is rather limited. Most of the BESSs utilize a low-voltage (around 50 V) Li-ion battery, which results in high current and requires the use of a transformer. Most likely, two-stage converters with galvanic isolation are used, limiting the overall efficiency of the system. The typical BESSs have the efficiency below 90%, whereas power electronic converters could be responsible for around half of power losses in the system. On the other hand, the low voltage batteries require simpler battery management and protection systems, making them less expensive and more feasible commercially. Because of these compromises, the current BESSs have strict limitations on the efficiency due to the use of low voltage batteries that are associated with high currents and more complex converter topologies. On the other hand, the batteries with increased voltages would enable the use of non-isolated topologies with potentially higher efficiencies. Several companies have already introduced such products to the market.

The typical power electronic interface of a battery with the grid is based on a two-stage configuration, comprised of a bidirectional DC-DC converter and a DC-AC inverter/rectifier connected via an intermediate DC-link. Modern Li-ion batteries can sustain current ripples associated with the grid frequency very well, even in single-phase systems. It is therefore possible to connect a battery of sufficiently high voltage to an inverter directly. Still, due to variation of battery voltage depending on its state of charge, the efficiency and power quality of such system is compromised. As a result, the intermediate DC-DC stage is still necessary to stabilize the DC voltage and obtain better performance.

With the possibility of using non-isolated converters to interface HV batteries, the standard approach would assume application of well-known DC-DC topologies, like buck, boost and buck-boost together with the grid inverter stage. This makes both of the two conversion stages process full power and exhibit high switching frequency, which still compromises the efficiency. One of the approaches that is widely addressed in recent studies is to use emerging solutions, like PPCs and FPCs at the DC-DC stage, which, as it is already reported, have been achieved extremely high efficiency values. However, the practical aspects, including transient operating modes, protection and cost, need to be evaluated further to justify this technology.

A range of alternative concepts utilizes a pulsating DC-link instead of the stabilized one. This brings the converter system closer to the single-stage converter, where only DC-DC stage operates with high frequency, while the grid-side inverter just unfolds the unipolar pulses into the sine wave and exhibits conduction losses only. A similar approach can be applicable to both single- and three-phase systems [145]. In addition, mixed concepts with fluctuating DC-link were also proposed, aiming to distribute losses more evenly between the stages [149]. On the other hand, it would be much more difficult to integrate other sources into such DC-link and therefore such solutions are generally suitable for AC-coupled BESS only.

Impedance source inverters are another group of topologies that allow voltage pre-regulation at a "virtual DC-link" before it is inverted into a sinusoidal waveform. Single-phase, three-phase and three-level configurations of these inverters were proposed in [150]. They can be more short-circuit-proof, as the shoot-through state is one of the inherent operating modes of such topologies. However, some studies show that the voltage stress on semiconductors and volume of components can be larger than for the standard two-stage configurations [151]. Moreover, only few studies address bidirectional operation of impedance-source converters [152,153].

In conclusion, there is a range of solutions for HV BESSs that are potential alternatives to standard buck-boost plus inverter configuration. The most optimal choice would evidently depend on the parameters of the system and its configuration. For the systems that incorporate a DC bus for integration of renewables and loads, a PPC/FPC with a bridge-type bidirectional inverter/rectifier seems to be a very promising solution. On the other hand, for an AC-coupled BES, the use of pulsating/fluctuating DC-link and unfolding inverter can bring an advantage in terms of switching loss and absence of a bulky capacitor. Still, the behavior of such configurations in practical applications, including transient modes and fault ride-through capabilities, needs to be addressed in more detail.

The configurations that include multilevel inverter topologies also seem quite promising for residential BESs. Despite generally being used in high-power applications, there are successful commercialization examples of this technology in residential applications. Recent works aim to bring such inverters on a new level, particularly taking advantage of developments in WBG semiconductors [115,116]. The systems with multilevel topologies potentially enable the use of battery stacks with lower voltage levels as compared to standard two-level inverters. This could result in a more optimal storage configuration. On the other hand, presently, the cost of WBG devices is still relatively high to make such multilevel inverters feasible in commercial BESSs.

The comparative analysis of evaluated power electronic interfaces is presented in Tables 3 and 4. The considerations above show that the most promising units of composite

BESS grid interface converters have somehow completing features (see Table 3 for details). For example, unfolding circuits provide neither DC regulation at the corresponding port nor AC half wave forming. This functionality, however, can be performed by a DC-DC converter. Multilevel converters without pulse mode control do not provide pulse mode regulation between levels, but partial power converters—provide regulation within a narrow range. Besides, the multilevel converters and unfolding units have no switching losses, but have significant conduction losses (Table 3). At the same time, the partial power converters can reduce both. A logical conclusion from the above is to combine the units with the adjacent features (Table 4).

**Table 3.** Losses of converters and energy conversion principles in BESS grid interface.

| Stage | Main Function | Peculiarities |
|---|---|---|
| Full Power Switch-Mode Rectifiers/Inverter (origin for comparison) | Forming AC | + Established technology, − High voltage input, high switching frequency, bulky filter |
| Full Power Switch-Mode DC/DC Converters | Forming DC | + Established technology, wide regulation range, − Full power operation, high switching frequency |
| Partial Power Converters | Forming DC | + Operation with part of rated power − Developing technology, limited regulation range |
| Multilevel Converters | Forming AC or DC | + Established technology, small grid filter − Control and hardware complexity |
| Unfolding Circuits | Commutation | + No switching losses − Developing technology, no regulation |

**Table 4.** Promising combination of converters to form BESS grid interface.

| Configuration | Advantages | Disadvantages |
|---|---|---|
| Single stage DC-AC Bidirectional Inverters/Rectifiers | Max. efficiency at a particular operation point | Lower efficiency at most of the operation points, Minimal battery voltage > amplitude of grid voltage |
| Impedance-Source Bidirectional Inverters/Rectifiers | Battery voltage pre-regulation Short-Circuit Proof | Voltage stress on semiconductors and volume of components is larger Complicated bidirectional operation Developing technology |
| Bidirectional inverter/ rectifier + Full Power DC-DC | Higher efficiency at the most of operation points, Wide battery voltage range, Allows integration of renewables into DC-link | Lower maximal efficiency, Both stages operate at full power and high switching frequency |
| Bidirectional inverter/ rectifier + PPC DC-DC | Higher efficiency at the most of operation points, Allows integration of renewables into DC-link, DC-DC operates with part of rated power | Narrow battery voltage range, Developing technology |
| Multilevel DC-DC and DC-AC | Low grid filter size and volume, Utilization of low voltage semiconductors, Modular design | High component count Complex control |
| Unfolder + Full Power DC-DC | Higher efficiency at the most of operation points, Wide battery voltage range, No switching losses in grid stage, No DC-link capacitor | No integration of renewables into DC-link |

## 6. Conclusions and Future Trends

This paper gives an insight into the field of storage systems for residential applications together with associated technologies and developments. To provide a broader view, the current state of these systems is addressed from multiple directions, including battery technologies, their market, standards, and grid interface converters.

Instigated by the on-going paradigm shift from centralized to distributed power generation, the storage technologies will become one of the key components of the future electrical grids that enable more optimal use of the conventional and local renewable energy sources and ensure the power supply security. However, a range of technological and regulatory barriers still stand in the way of these systems, limiting their benefits and potential.

Today's market for dedicated residential storage systems is still in the process of being established. It is currently very dynamic, and several manufacturers have already introduced and commercialized their solutions, with more companies and products being announced and trying to enter the market every year. Still, the price for residential solutions is relatively high for a private client, while the return of investment is not evident in many cases.

The developments and price reduction of Li-ion battery technologies are mainly driven by massive transportation electrification and this trend will continue in the following years. Despite the distinct potential of vehicle to grid (V2G) solutions, they are unlikely to be able to replace stationary battery systems and their functions due to economic reasons, mainly related to lifetime and cycle-cost. Nevertheless, the use of second-life Li-ion batteries for stationary storage has certain potential.

Batteries based on the Li-ion technology are currently dominating the market, however, at a certain point, the price and performance of other battery technologies, like flow batteries, is likely to make them a more expedient choice for larger-scale stationary solutions.

According to our analysis, the majority of commercial residential storages are currently using low voltage batteries with voltages of around 50 V, mainly due to the cheaper price per kWh. These batteries are typically interfaced with the grid by means of a power electronic converter with a transformer to provide required voltage matching and galvanic isolation. However, the mass production of HV EV batteries along with their second-life use is likely to make the HV stationary storage solutions more popular in the residential sector. This would make the use of non-isolated interface converter topologies attractive due to their typically lower component count and higher efficiency. In addition to standard and typically used topologies, like buck-boost or bridge, which are rated for full power of the system, the recent research interest is also focused on partial- (fractional-, differential-) power converters. Such topologies have the potential to offer even further improvement of efficiency in various operating conditions.

Presently, many countries are introducing initiatives that are either directly (by subsidies) or indirectly (via marginal feed-in tariffs) encouraging the use of local energy storage. Moreover, a range of standards is being developed to regulate the use of such systems and facilitate unleashing of their full potential. In addition to basic renewable energy self-consumption increase, battery-based storage systems can provide uninterruptable power supply functionality, offer ancillary grid service support, enable peer-to-peer energy trading etc. Together with the large-scale global investments in the battery technologies it is highly likely that in the following decades, the residential battery systems will follow the route of photovoltaics and become an essential and inherent part of the future power grid.

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