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Published in:
IEEE Journal of Emerging and Selected Topics in Power Electronics

Link to article, DOI:
10.1109/JESTPE.2022.3208689

Publication date:
2023

Document Version
Peer reviewed version

This article has been accepted for publication in IEEE Journal of Emerging and Selected Topics in Power Electronics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JESTPE.2022.3208689

DC-DC Converters for Bipolar Microgrid Voltage Balancing: A Comprehensive Review of Architectures and Topologies

V. Fernão Pires, *Senior Member, IEEE,* A. Cordeiro, C. Roncero-Clemente, *Member, IEEE,* Sebastian Rivera, *Senior Member, IEEE,* Tomislav Dragičević, *Senior Member*

***Abstract*— DC microgrids initiated the change of a paradigm regarding the concept about electrical distribution networks, especially in the context of the distributed generation associated to renewable energies. However, this new reality opens a new area of research, in which several aspects must be carefully studied. Indeed, the bipolar design is one of the principal dc microgrid configurations considering its characteristic wiring. Although holding many promising advantages, the bipolar dc microgrid has a tendency towards voltage and current imbalances due to the unequal distribution of the loads and generators between the two poles. Thus, specific power-electronic-based solutions are required to ensure the balance of these dc microgrids. Within this frame, this article gives a comprehensive review of the multiple architectures and power electronic topologies proposed to mitigate/eliminate this undesired condition. The following provides an insightful classification and discussion with the pros and cons of these solutions. This work can serve as a timely review for researcher/engineers who want to enter the voltage balancing field in the bipolar dc grids and promote the innovation of their power-electronics-enabled solutions.**

***Index Terms*— Bipolar dc microgrid, dc-dc converters, smart grid, unbalanced grid, voltage balancer.**

I. Introduction

THE ADVANCEMENTS in newer technologies along with the search for sustainability has paved the way for distributing power in dc. The modernization of electronic loads along with the proliferation of renewable energy sources (RES) and energy storage systems (ESSs) has brought the attention towards the development of compact, highly efficient, reliable, and robust dc distribution networks [1]. Emerging technologies such as electric vehicles (EVs) and their charging infrastructure [2,3], modern data centers [4,5], dc powered buildings [6-8] or green hydrogen technologies (electrolysis and fuel cells) [8,9] are better suited for dc systems. Currently, the dc microgrid concept has prevailed as the main candidate to accommodate fast changing loads and embrace the distributed RES, to support and alleviate the modernization of the electric grid [10,11].

Bipolar dc microgrids can be conceptualized taking into consideration their connection with the utility grid as in Fig. 1 (a) or operating in the islanded mode as in Fig. 1 (b). Focusing on the second option, at least one sufficiently large ESS must be installed or, on the contrary, the oversizing of some of the RESs may be necessary to always ensure power balance. Another underlying issue is the control of the system. There are efforts in standardizing dc voltage levels [12], thus the tight margins around a dc bus nominal voltage level must be guaranteed for a safe and reliable operation of both the networks and user´s facilities. Depending on the nature of the grid, the complexity of the control system usually increases, originating additional hierarchical and advanced control algorithms with extra-measurements over the microgrid [13], [14].

Among the mainstream configurations for dc microgrids, the bipolar approach presents several advantages in terms of flexibility, reliability, and safety over the unipolar counterpart as originally proposed in [15]. Among their main features, bipolar grids reduce the magnitude of the voltages with respect to ground, besides allowing the connection of larger loads to their full voltage. For example, considering a bipolar dc network with ±170 V, it is possible to use a voltage source with 170 V or with 340 V, hence its flexibility is enhanced. Also, in the presence for short-circuit faults it offers an easier and faster clearance given the presence of the neutral conductor [16]. Moreover, it improves the reliability of the power supply since

This research was funded in part by the Junta de Extremadura (Spain) with the project (IB20165), the program "Ayudas Talento" (TA18003), and by national (Portugal) funds through FCT - Fundação para a Ciência e a Tecnologia, under project UIDB/50021/2020. Also, financial support from the Agencia Nacional de Investigacion y Desarrollo (ANID) through the projects: FONDECYT 1220346, AC3E (ANID/Basal/FB0008) and SERC Chile (ANID/FONDAP/15110019) are greatly acknowledged. (Corresponding *author: C. Roncero-Clemente).*

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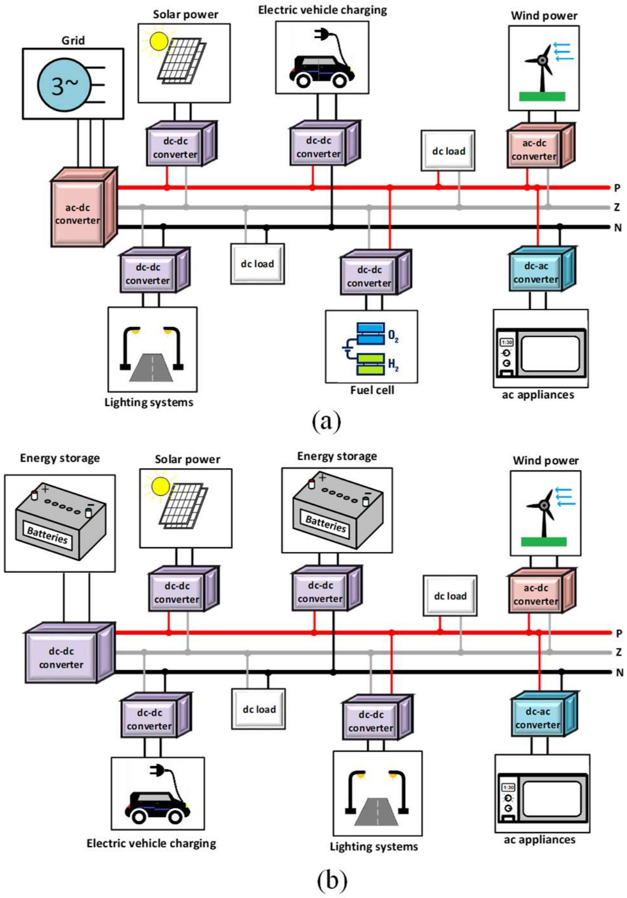

Fig. 1. Bipolar dc microgrid. (a) Connected to the grid. b) Operating in islanded mode.

the distribution of the loads is implemented by the connection to different power lines. In this way, if a failure occurs in one set of the supply lines, then the loads connected to the other set of supply line are not affected. Finally, this dc distribution scheme is compatible with existing three-phase installations cabling with 5 conductors. This can be seen as an easier retrofitting process while maintaining most of the existing infrastructure.

The remainder of this work is organized as follows. Section II presents the general features of bipolar dc microgrids, including an explicit description of the problem related to its voltage imbalance. Section III covers a deep topological review of the different solutions adopted to mitigate or eliminate the voltage imbalance. In there, many illustrations are arranged. Section IV is devoted to a valuable comparison set of tables and to discuss the particular solutions. This section is considered the core of the article. Finally, Section V presents a summary of the study highlighting the main contributions.

II. Challenges in Bipolar DC Microgrids

Due to aforementioned reasons, these networks are proposed and used in several applications, such as, dc distribution, large data centers, homes and buildings, electric ships and also in electric aircrafts [13], [17]–[20]. These grids can also be a suitable option in the charging infrastructures associated to EVs. The bipolar configuration can play a vital role to supply fast EV charges due to the high power associated, avoiding adverse effects on the grids [21]. At the same time, ESSs could be easily integrated to this facility and contribute to the same purpose. However, there are still some disadvantages inherent to the dc bipolar wiring. One of the disadvantages is that requires an extra wire. However, the main disadvantage is related with the voltage unbalance that can appear between the bipolar poles [22]. During its operation, the loads with different nominal powers can be connected either to the upper or lower pole, thus the voltage level of each pole tend to change to different values originating a voltage imbalance. This problem can be further aggravated if the distributed generation only connects to the upper or lower pole. Subsequently, this undesired situation leads to the development of new solutions, which are essentially based on power-electronic converters specifically designed for the balancing purpose.

A. Imbalance in Bipolar DC Microgrids

As previously mentioned, the bipolar dc microgrids are characterized by a flexible connection of loads and power sources installed in three ways: i) positive-to-zero (PZ), ii) zero-to-negative (ZN) and iii) positive-to-negative (PN). Both the loads and sources will interact, and the equivalent effect of asymmetric operation can be represented by the following single-source single-load diagrams. The problem of the imbalance does not appear in three situations. Namely, if both the sources and loads are PN connected (see Fig. 2 (a)), or PZ or ZN connected (as indicated in Fig. 2 (b) and in Fig. 2 (c), respectively), then no problem associated to voltage imbalance will occur.

However, if asymmetric consumption arises, then the voltage imbalance will appear if no balancing measures are taken. Situations that generate the dc microgrid voltage imbalance are depicted in Fig. 3. Each kind of equivalent connection produces a typical voltage imbalance [23]. Therefore, if the voltage source and load are commonly connected to the Z pole (Fig. 3 (a) and (b)) then the fault is designated as a type A voltage imbalance. However, if the voltage source and load are commonly connected to the P pole, as indicated in Fig. 3 (c) and (d) respectively, then it is designated as a type B voltage imbalance. The type C corresponds to the voltage source and load commonly connected to the N pole as shown in Fig. 3 (e) and (f).

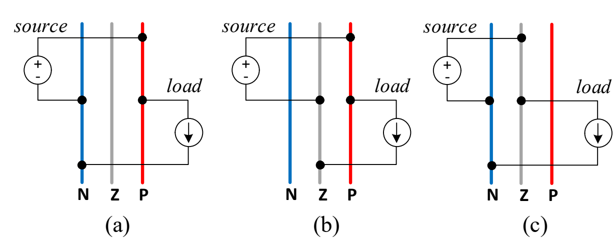

Fig. 2. Source and loading conditions that avoid the voltage imbalance problem. (a) The sources and load are connected in PN. (b) The sources and loads are connected in PZ. (c) The sources and loads are connected in ZN.

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Specially for islanded grids, these imbalances can lead to severe problems. Namely, if the converter-interfaced assets are asymmetrically connected, then the voltage imbalance in the microgrid can reach intolerable values [23]. It should be noted that, since the loads are usually dynamically connected and disconnected, at the limit case, all of them may be connected to the positive or to the negative pole. This can have impacts in the protection system and may result in the disconnection of sectors or even the whole microgrid. On the other hand, dc-dc equipment will not operate at their nominal conditions, leading to reduced efficiency and reliability, or more importantly get damaged by overvoltage.

There are different solutions with the aim of mitigating or eliminating this problem. One possibility is based on the incorporation of an extra equipment to the bipolar dc microgrid, namely the voltage balancer. The other possibility is based on additional sources or loads connected to the three poles, instead to only two. The next section reviews these possible solutions.

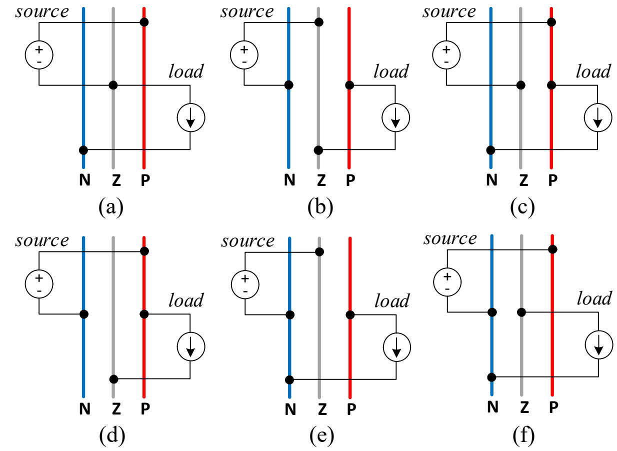

Fig. 3. Six different connections that generate bipolar dc microgrid voltage imbalance. (a) and (b) Imbalance type A. (c) and (d) Imbalance type B. (e) and (f) Imbalance type C.

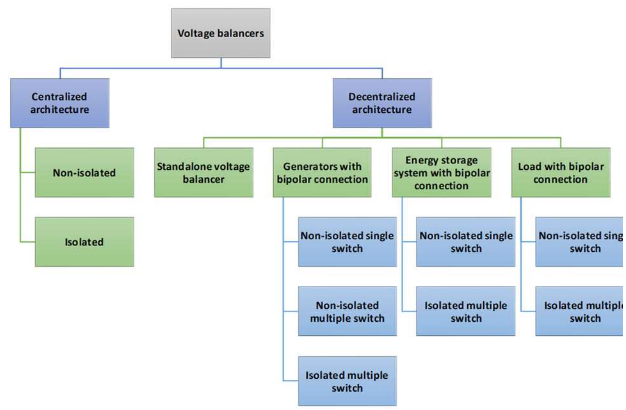

Fig. 4. Proposal for the classification of voltage balancers in bipolar dc microgrids.

B. Applications of Bipolar DC Microgrids

Due to the advantages previously referred, bipolar have been used in several applications. One of the applications in which this type of microgrid has been implemented are power distribution systems for data centers [24]. The typical voltage in these cases is ± 190 V. Also, these grids have been deployed in applications for more electric aircraft. An example of this can be seen in the Boeing 787 aircraft, which features a bipolar voltage ± 270 V dc [25]. Another area with great potential is for the household and building applications. In [16] is presented a real application in which a dc voltage of ± 170 V was used. These bipolar dc microgrids are also suitable for ships. Several studies have been conducted with these kinds of microgrids. Moreover, there are already established recommendations regarding the medium voltage dc (MVDC) voltage levels for shipboard microgrids [26]. Finally, these grids have also been considered for electric vehicle charging stations [17, 21]. In this case, the use of voltages higher than ± 269 V dc is recommended [7]. Table I summarizes the aforementioned emerging bipolar dc microgrid applications and their respective voltage levels.

III. Power Converters and Solutions: The Voltage Balancer in Bipolar DC Microgrids

The stabilization of the dc buses in a microgrid can be pursued through different approaches. The equipment designated as a solution for the dc voltage imbalance in microgrids is known as the voltage balancer. Depending on the configuration of this equipment, different architectures and types can be extracted from the literature. A very simple way to classify these voltage balancers is proposed in Fig. 4. Roughly, the voltage imbalance mitigation/elimination can be achieved by means of a special extra equipment or using bipolar dc-dc power converters for generators, ESSs and/or loads, which can inject/demand energy in a balanced or unbalanced way into/from the microgrid. During the last decade, the study of these voltage balancers is getting further advances thanks to the rapid development of the dc technologies oriented to microgrids. This effort has triggered many proposals with different topologies and their associated control algorithms. In this point, and following the division of Fig. 4, the different circuitries will be illustrated below. The voltage balancer (see Fig. 5 (a)), in essence, is a power-electronic circuit that is characterized by power electronic semiconductors and energy storage elements as inductors and capacitors. Their only purpose is to transfer energy from the positive pole to the negative pole or vice versa, depending on the voltage imbalance type, as indicated in Fig. 3. Thus, this device can be represented

TABLE I
Applications and Voltage Levels of Typical Bipolar DC Microgrids

Application	Voltage level
Data Centers	±190V
Aircraft Systems	± 270 V
Household	± 170 V
Shipboard	± 750 V or ± 1500 V
Electric vehicle charging station	> ± 269 V

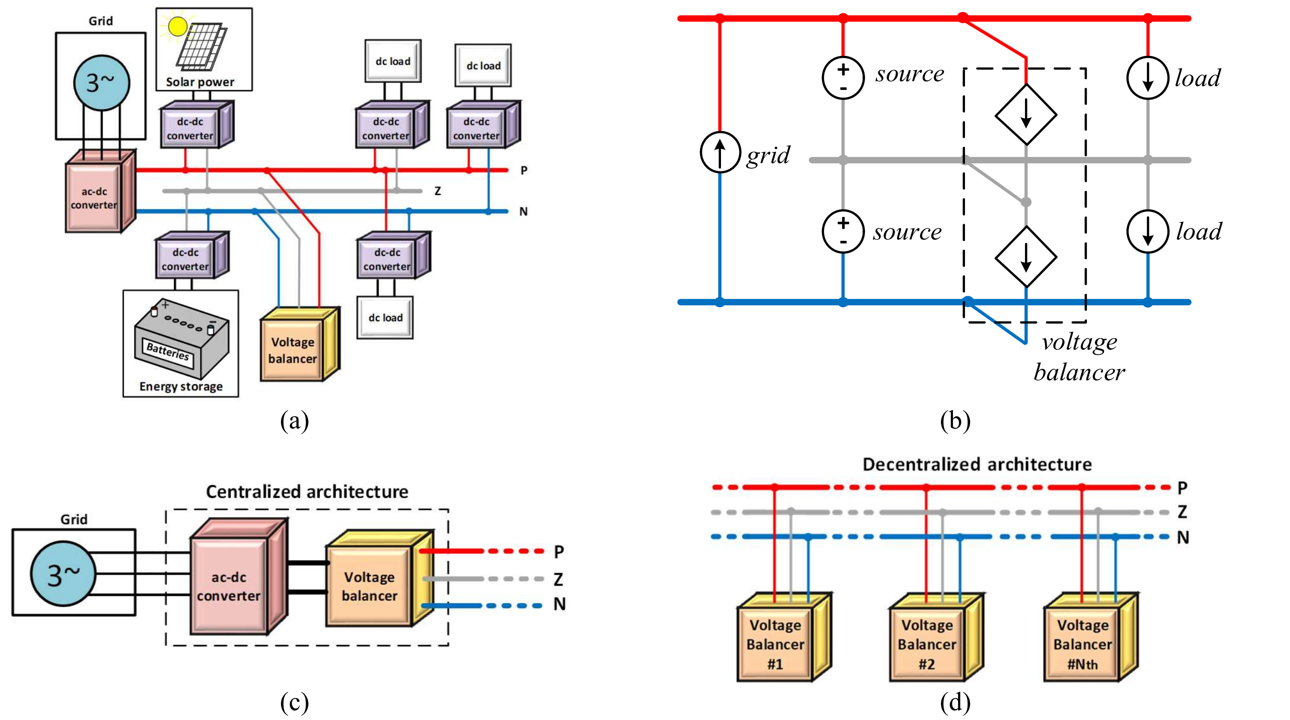

Fig. 5. Voltage balancers. (a) Block diagram and its placement in a bipolar dc microgrid. (b) Equivalent circuit. (c) Centralized architecture. (d) Decentralized architecture.

by an equivalent circuit that consists into current-controlled sources (Fig. 5 (b)) or voltage-controlled sources connected to each of the three poles [27].

Voltage balancers can be listed into two main architectures: 1) centralized and 2) distributed. In the first case, only one voltage balancer associated to the converter that interfaces the ac utility grid is placed. This architecture has a clear disadvantage, especially in dc microgrids with long lines. At the furthest point from the centralized voltage balancer placement, there may be a significant voltage imbalance due to the voltage drops on the lines. To overcome this, a second architecture that places several voltage balancers at the weakest points of the microgrid can be planned. In this configuration, the price to pay is a higher cost, as several voltage balancers are required along the dc lines. In the next subsections, an extended review of the power topologies for centralized (Fig. 5 (c)) and decentralized (Fig. 5 (d)) solutions is conducted.

A. Centralized Architecture

The centralized architecture is one of the most common configurations to provide voltage support in bipolar dc microgrids despite the disadvantages pointed out earlier. According to Fig. 4, the power circuits of these voltage balancers are distinguished between non-isolated (with three voltage levels) and isolated. Below, the first group presented is focused on the non-isolated topologies. Then, the isolated ones are illustrated.

The simplest non-isolated topology is the buck-boost or half-bridge type centralized voltage balancer presented in Fig. 6 (a). The symbols P, Z and N denote the positive, zero, and negative terminals, respectively. This voltage balancer can balance the middle (zero) terminal voltage through the operation of power devices S_1 and S_2 to boost or buck the voltage supplied by the rectifier. It has been widely applied and usually placed as a second stage to unidirectional or bidirectional grid rectifiers [16], [28] or in aircraft power systems [20]. Despite its simplicity, it presents as main disadvantage the relatively high current ripple in the inductor and the bulky dc-link capacitors. At the same time, this converter has a reactive circulating current flowing between the input and output terminals when there are two loads connected at the bipolar output under slightly unbalanced conditions. A similar but improved buck-boost voltage balancer is the circuit of Fig. 6 (b). It is also able to post-regulate the input dc voltage supplied by the rectifier, thus the bipolar side can be fed with a total voltage lower than the input dc voltage [29]. The main advantage is the reduction of the turn-off switching losses in comparison with the previous topology. Despite the extensive use, the buck-boost voltage balancers also suffer from shoot-through problems, that is considered the major drawback affecting to the reliability of this power converter and consequently of bipolar dc microgrids. To face this issue, several topologies derived from the classical buck-boost type were proposed. One of them is the dual buck-boost voltage balancer illustrated in Fig. 6 (c) [30]. The freewheeling current goes through the independent freewheeling diodes instead of the body diode of the main switches. At the same time, the switches, and diodes block half of the dc-link voltage, thus the losses are reduced. Nevertheless, it requires a higher number of components compared to the centralized buck-boost type balancer. Note that in some of the following figures, the connected rectifier and the three-phase grid are not represented

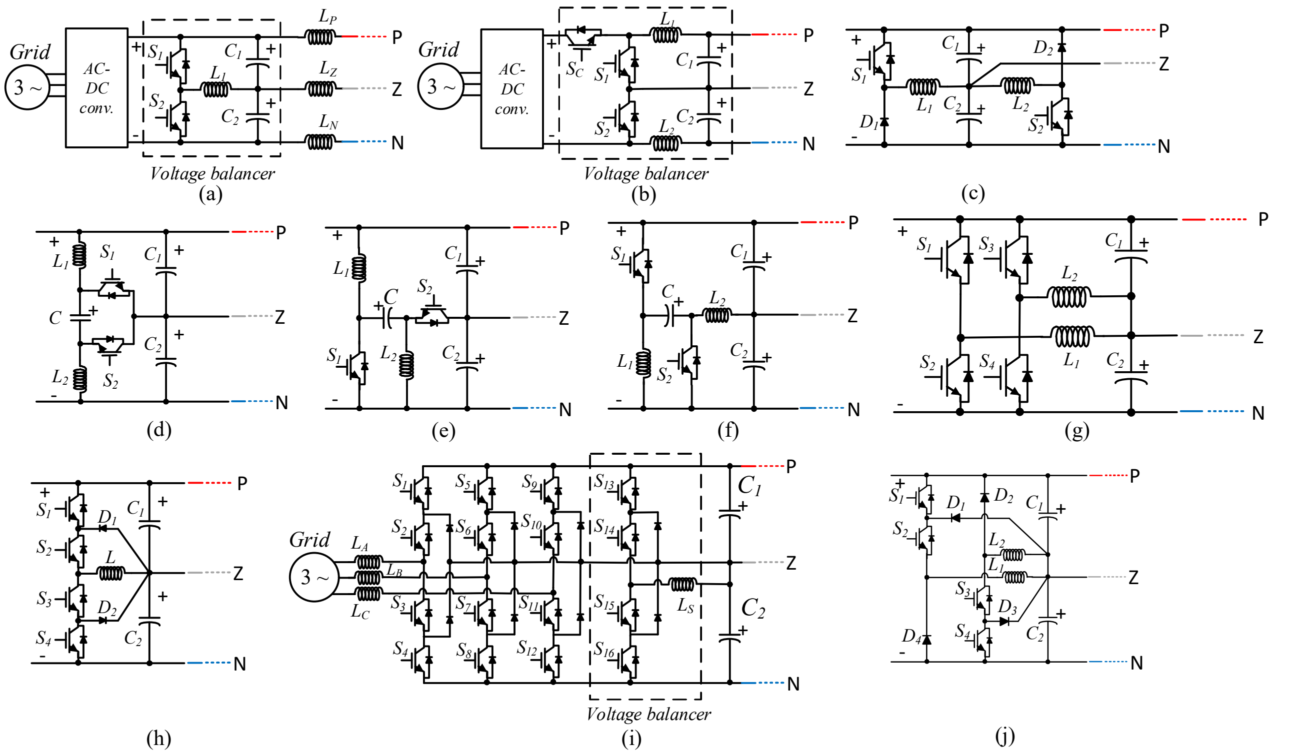

Fig. 6. Non-isolated voltage balancers in dc bipolar applications with centralized architectures. (a) Buck-boost type. (b) Improved buck-boost type. (c) Dual buck-boost topology. (d) Bidirectional *Ćuk*-type derived circuit. (e) Bidirectional *Super-SEPIC* derived circuit. (f) Bidirectional *Super-Zeta* derived circuit. (g) Interleaved approach. (h) Three-level buck-boost type. (i) Three-phase NPC converter with a three-level buck-boost type [21]. (j) Three-level dual buck-boost topology.

for simplicity.

Another topology adopted as centralized voltage balancer was derived from the bidirectional *Ćuk* converter [20], [28]. Despite a larger device count (Fig. 6 (d)), this voltage balancer operates with a lower inductor current as the load current is split between each inductor. Another advantage is that the shoot-through of switches is eliminated. With similar features, two different converters namely the *super-SEPIC* and the *super-Zeta* types of voltage balancers (shown in Fig. 6 (e) and (f) respectively), are aiming to improve the performance of the centralized solutions. They are derived from the bidirectional *super-SEPIC* and *super-Zeta* power converters. These two-voltage balancers also belong to the family of high-order converters and, therefore, have no shoot-through problems [28]. On the other hand, some interleaving approaches have been proposed, aiming to mitigate the influence of the current ripple in classical voltage-based topologies [20], [28]. In this interleaved buck-boost voltage balancer (Fig. 6 (g)), the average value of the total ripple currents flowing from the inductors to capacitors can be zero, thus capacitances C_1 and C_2 are greatly reduced. Other interleaved buck-boost topology with n legs [31] and with coupled inductors have also been developed [32]. Such topologies provide extended solutions to higher voltage unbalances in bipolar dc microgrids using different current sharing ratios and optimized strategies.

For a higher voltage levels and/or reduced voltage stress, there are some options for voltage balancers based on multilevel configurations. They are usually based on the existing multilevel dc-dc converters or from the existing two-level voltage balancers. Fig. 6 (h) shows a three-level buck-boost voltage balanced obtained by adding two switches and two clamping diodes to the two-level topology [15], [28], [33]. This circuit also suffers the potential shoot-through states and a high current ripple. It has been tested in EV charging stations with bipolar dc configuration (Fig. 6 (i)) [21]. The three-level dual buck-boost voltage balancer depicted in Fig. 6 (j) presents a more complicated configuration and requires a sophisticated control strategy [34]. Nevertheless, it does not have nor the shoot-through problem neither the reactive circulating current under slightly unbalanced operations.

The dc microgrids are normally designed to be interfaced with an ac grid and/or other RESs in order to improve the availability of power into the microgrid. This fact can create some operational and safety problems related with the system grounding [12], [16]. Electric shock hazards and a high neutral voltage fluctuation may appear because the common mode voltage operation, creating new current loops associated to the converters connected to the same dc bus. The selection of a proper grounding configuration for a dc microgrid system is much more complicated than in its ac counterpart [35]–[37]. To solve it, several topologies with galvanic isolation have been used as a solution in centralized voltage balancers. One of the most straightforward isolated solutions is the conventional dual-active-bridge (DAB) converter combined with the

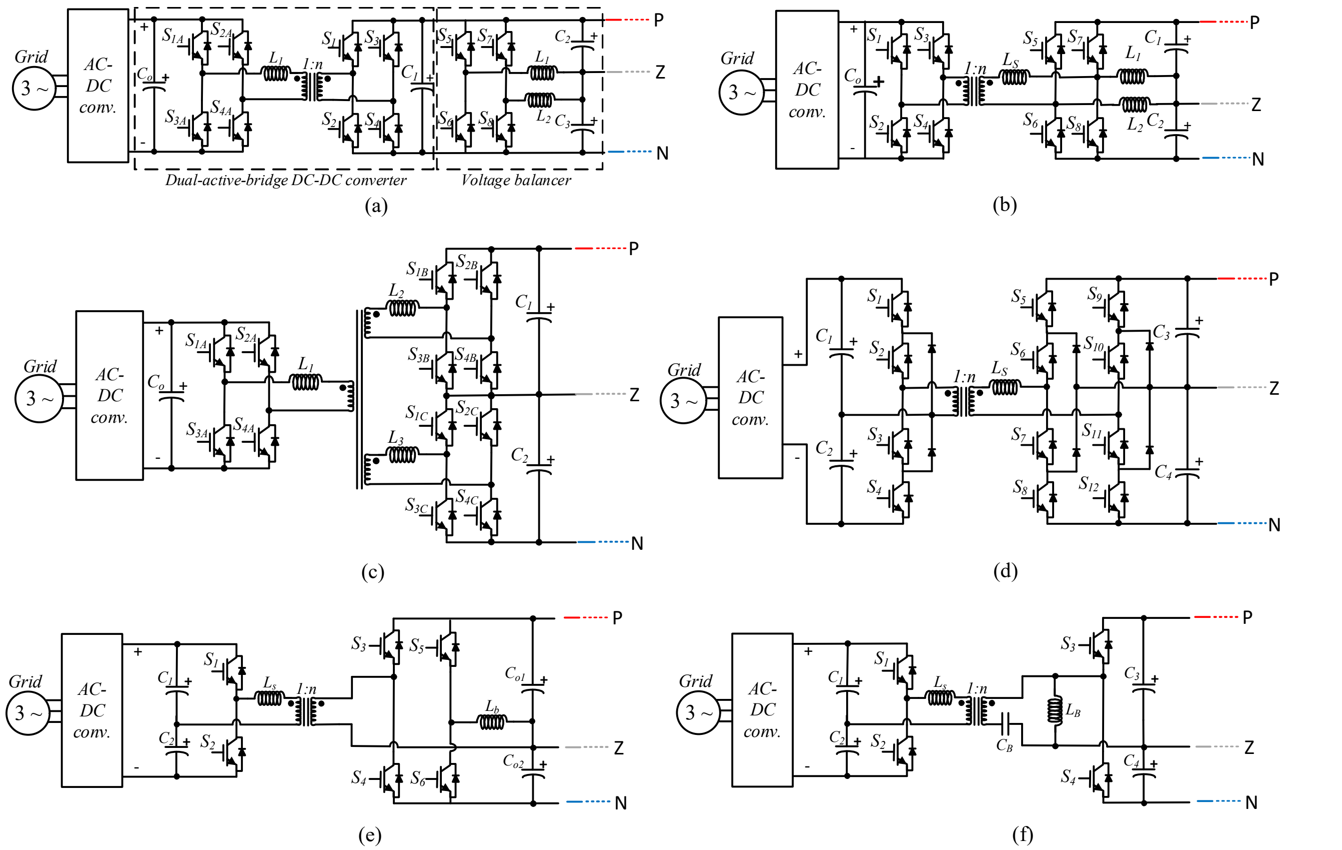

Fig. 7. Isolated voltage balancers in dc bipolar applications with centralized architectures. (a) DAB with two power conversion stages. (b) DAB composed by a single stage. (c) Series of two-level DAB (DAB+DAB). (d) Solution derived from the single-stage three-level converter. (e) Dual-active-half-bridge (DAHB) converter with inductor/capacitor voltage balancer (LCVB). (f) Isolated dc–dc converter with buck–boost voltage balancer.

interleaved buck-boost voltage balancer [38]. This circuit consists of two power conversion stages. The first one is composed by two full-bridges with a high-frequency transformer regulating the dc voltage, connected to a voltage balancer dedicated to the bipolar dc microgrid, as indicated in Fig. 7 (a). The existence of two power conversion stages degrades the power density, the power conversion efficiency, and the cost-effectiveness of voltage balancers. In this sense, other configurations have been designed by using only one stage, which can regulate and balance dc voltage level without the additional voltage balancers [38]. For example, only two extra dc inductors are included in the proposed DAB converter in Fig. 7 (b). At the same time, it can fully obtain balanced bipolar voltage level under the entire unbalanced load condition using the dc offset currents through the dc inductors, besides operating at zero voltage switching (ZVS). A similar configuration was recently proposed [39]. The next voltage balancer is composed by a high-frequency galvanic isolated series of two-level DAB, known as DAB+DAB [40] (Fig. 7 (c)). This circuit is based on the triple-active bridge (TAB) and presents the twice static gain of an equivalent bridge (DAB) topology, and the semiconductors of the bipolar side are subjected to half of the total bus voltage. It also presents a simple and centralized control which allows to connect ESSs, sources or loads in any of its ports. However, it requires a high number of active switches, sensors, a three-winding transformer, and complex control for voltage balancing. A single-stage three-level voltage balancer that only requires a two winding transformer to balance a bipolar dc microgrids is illustrated in Fig. 7 (d) [41]. It is derived from the three-level DAB converter without additional circuits, being controlled with an enhanced switching modulation to ensure the proper balancing. It also requires a high number of active switches but on the bipolar side they only are subject to half of the total voltage bus. In Fig. 7 (e) [40], it is proposed a dual-active-half-bridge (DAHB) converter. This converter presents a simple structure since only adds an inductor and a capacitor to the conventional DAHB converter for voltage balancing. With the added inductor/capacitor voltage balancer (LCVB), the proposed converter can achieve voltage balancing without any feedback control or extra active switches. The same phase-shift control as used in the DAHB converter is applied to the proposed converter. However, the semiconductors of the bipolar side must support the total bus voltage. Alternatively, a solution developed toward reducing the number of active switches is the one displayed in Fig. 7 (f) [40]. It is an approach that connects a buck–boost converter-based voltage balancer to the output of the isolated dc–dc converter. For its regulation, a simple pulse-width-modulation (PWM) scheme is needed, however, the buck–boost converter-based voltage balancer still

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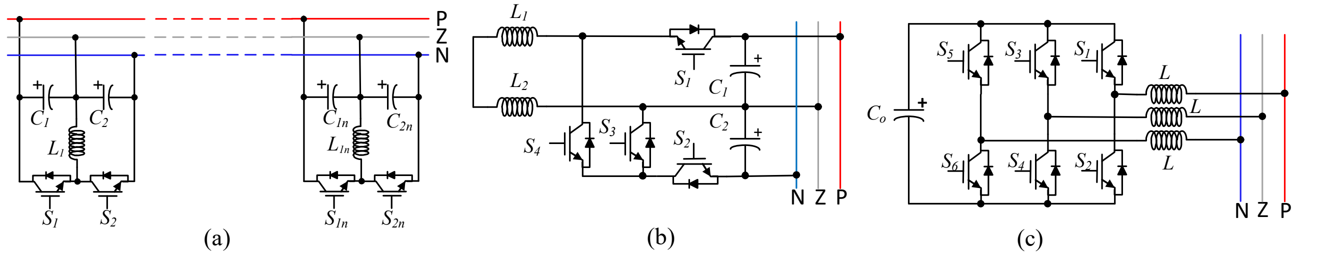

Fig. 8. Voltage balancer as standalone solutions for bipolar dc microgrids. (a) Buck-boost circuits. (b) Modified SC converter. (c) Current redistributor.

requires extra switches, which degrades the system efficiency and power density. Recently, some interesting solutions based on multi-port structures allow the integration of more than one distributed energy resource [42], [43]. Finally, it is worth noting the approaches proposed in [44] and in [45]. Beside the power converter, they include an ac-side grounding inductors allowing for an independent dc-pole control. The decoupling of power flows is exploited as a pole voltage balancing mechanism.

B. Decentralized Architecture

As a measure to overcome the problems associated to the centralized voltage balancers, especially at the points located farther from their placement, the use of decentralized architecture was briefly disclosed above. According to Fig. 4, decentralized architectures can make the voltage support to by means of a dedicated or distributed set of voltage balancers, or by featuring bipolar dc-dc stages for all the equipment interfacing the grid.

1) Standalone voltage balancer

Like the centralized system, the buck-boost topology is a classical solution to balance long bipolar dc microgrids [46]. Controlling the PWM of power devices S_1 and S_2 depending on the desired balance control strategy, it is possible to store energy in the inductor and then release the energy to the other pole (Fig. 8 (a)). Other topologies such as dual buck-boost, interleaved buck-boost, three-level buck-boost, three-level dual buck-boost, *Ćuk*, *Super-SEPIC* or *Super-Zeta* can also be adopted as standalone voltage balancer, as previously stated. Fig. 8 (b) represents the modified series-capacitor (SC) dc-dc converter [47]. Its operational principle is similar to the classical buck-boost topology but with asymmetrical operation regarding the power devices. This circuit incorporates more power switches, which permits the bidirectional dc-dc power flow between the dc bus and the ESS (more details will be further given). In addition, if there is no power flow between the dc buses and the ESS (or it does not exist), the proposed circuit can compensate unbalanced power with extended voltage range. The current redistributor represented in Fig. 8 (c) is also installed as possible solution in this family [29], [48]. Some of the advantages of this converter is the minimization of the transmission losses in long bipolar dc lines. The control scheme is designed with a current feedback control loop; thus, it can guarantee a null current flowing through the zero terminal. The active damping of common (CM) and differential (DM) mode line resonances are also guaranteed. Finally, the integration of any ESS and its performance during the loss of one dc bus line can be achieved.

2) Generators with bipolar connection

As a difference with the previous dedicated voltage balancers, there are other options that do not require an extra converter. Instead of using a dc-dc converter with a single output port, some generators can contribute to the voltage support using the multiport dc-dc bipolar converter. A generator can be understood as a photovoltaic (PV) array, wind turbine or fuel cell-based (FC), that is, just unidirectional power flow is feasible. These topologies must be designed and controlled in a way that the generated power is injected into the pole with lower voltage. Fig. 9 outlines the possibilities in accordance with the balance/imbalance condition of the bipolar dc microgrid. Thus, if the voltage of the positive pole is lower in magnitude than the negative pole, then all the energy is transferred to the positive pole (Fig. 9 (a)), otherwise the generated energy will be injected to the negative pole, as indicated in Fig. 9 (b). Then, Fig. 9 (c) shows the desired power exchange in a balanced microgrid, that is, the power is injected to both poles in similar way. There is a special operation if the generator is capable to ensure the global balance. In this case, the dc-dc converter must transfer energy to both poles in an unbalanced way. Fig. 9 (d) and (e) illustrate these conditions, when the positive or the negative pole requires a higher support respectively.

These converters associated to generators can also be listed

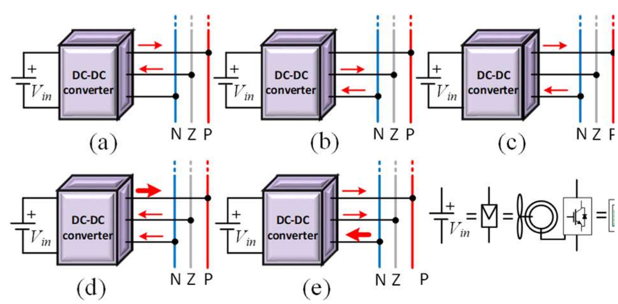

Fig. 9. Possibilities for the energy transfer between the generator and the microgrid. (a) Higher voltage in positive pole. (b) Higher voltage in negative pole. (c) Balanced operation. (d) Unbalanced operation with higher voltage in positive pole. (e) Unbalanced operation with higher voltage in negative pole.

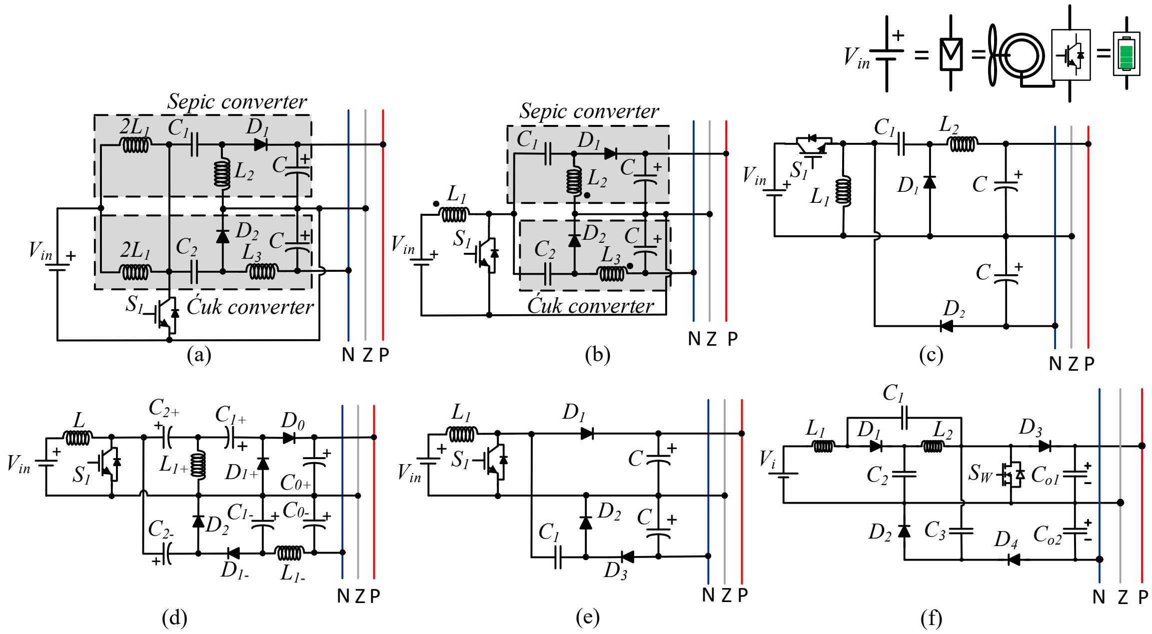

Fig. 10. Single-switch topologies for bipolar connection in generators. (a) *Ćuk-SEPIC* converter. (b) *Ćuk-SEPIC* with integrated magnetic cores. (c) Buck-boost *Zeta* converter. (d) Voltage lift technique with double-output converter. (e) Boost with self-lift converter. (f) Solution derived from the quasi-Z converter.

as non-isolated or isolated. The latter are adopted if the application requires a high-voltage-gain ratio or the isolation between the source and the grid. Non-isolated solutions are used for low voltage dc microgrids with reduced voltage gain ratio requirements due to the reduction in size, cost, and losses. Nevertheless, some topologies without galvanic isolation and higher voltage gain have also been developed.

Most of the non-isolated topologies are formed by two dc-dc converters; however, they are usually merged to use a single switch. With the main purpose of illustrating this family of decentralized voltage balancers with a single switch, Fig. 10 shows the solutions found in the literature. Two options based on the *Ćuk-SEPIC* are presented in Fig. 10 (a) and (b) [49], [50]. Their main difference underlies in the use of integrated magnetic cores to reduce the input current ripple. Another solution that combines the buck-boost with the *Zeta* converter is depicted in the Fig. 10 (c) [51], [52]. Each of its outputs has a gain equal to the value obtained with the buck-boost cell. The voltage lift-type mirror-symmetrical double-output dc-dc converter was proposed to increase the voltage gain ratio [53] (Fig. 10 (d)). However, this circuitry shows a higher number of passive elements. Alternatively, the topology shown in Fig. 10 (e) is based on the boost-cell with self-lift, and overcomes this drawback [54], [55]. Finally, a high-voltage gain voltage balancer using a single power switch is highlighted in Fig. 10 (f). This concept was derived by the mature quasi-Z topology to support bipolar dc buses [56].

In addition, other solutions involving more than one switch can also be used as generator interfaces with support to bipolar dc microgrids. One of the topologies that better suits is the three-level dc-dc converter. The three-level boost converter (Fig. 11 (a)) allows to transfer the energy in a balanced or unbalanced way depending on the power switching [57]. Other three-level structures based on the buck-boost and *SEPIC* are illustrated the Fig. 11 (b) and Fig. 11 (c) providing both buck and boost operation, respectively [57]. The input current of the former solution is discontinuous; thus, some limitations appear in certain applications such PV generators, demanding additional input filters. The combination of two dc-dc converters with the input-parallel output-series converter is displayed in Fig. 11 (d) [58], [59]. This converter has some advantages including low input current ripple, low voltage stress for power semiconductors, and high voltage-gain. In addition, the potential difference between the output and the input sides of this converter is a capacitor voltage rather than a high frequency PWM voltage. Other proposals (Fig. 11 (e) and Fig. 11 (f)) merging two topologies and with opposite polarity configuration are also used, as the combination of the buck-boost with the *Zeta* circuit or the *Ćuk* with *Zeta* [57]. Conversely, the three-level quadratic boost in Fig. 11 (g) allows a higher voltage gain with independent output regulations [60]. Alternatively, interleaved approaches have also been covered given their reduction in the high-frequency ripples and improved dynamic response. In this type, the interleaved association between *Ćuk* and *SEPIC* includes more passive components and power semiconductors [61] (see Fig. 11 (h)). The last group of topologies for generators with bipolar connections is dedicated to the isolated circuits. There are a few of this kind of power circuits, normally used with a very high voltage ratio requirement. The dual output *Ćuk* converter has two symmetrical output voltages and galvanic isolation [62], at the expenses of a significant number of passive components (Fig. 12 (a)) when compared to the integrated *SEPIC* with a flyback converter [63] (Fig. 12 (b)). Both topologies feature continuous input current, which make them suitable for PV or FC generators. A similar solution that requires even a smaller

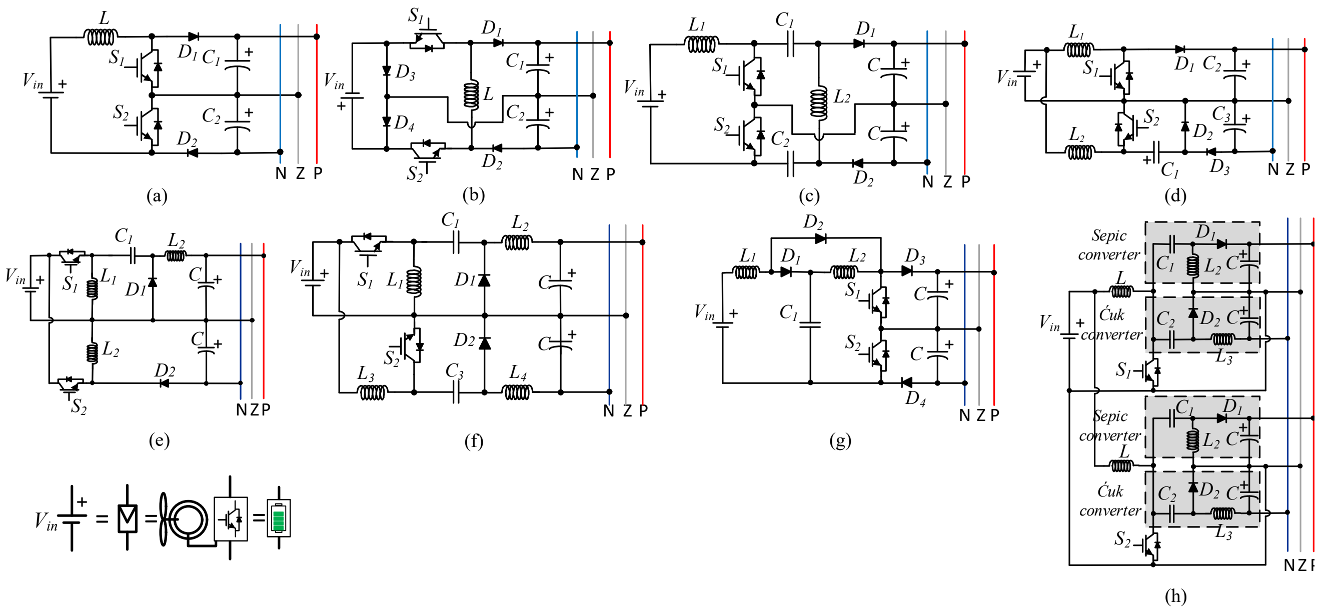

Fig. 11. Multiple-switch topologies for bipolar connection in generators. (a) Three-level boost converter. (b) Three-level buck-boost converter. (c) Three-level *SEPIC* converter. (d) Input-parallel output-series dc-dc boost converter. (e) Boost *Zeta* converter. (f) *Ćuk-Zeta* converter. (g) Three-level quadratic boost converter. (h) Interleaved *Ćuk-SEPIC* converter.

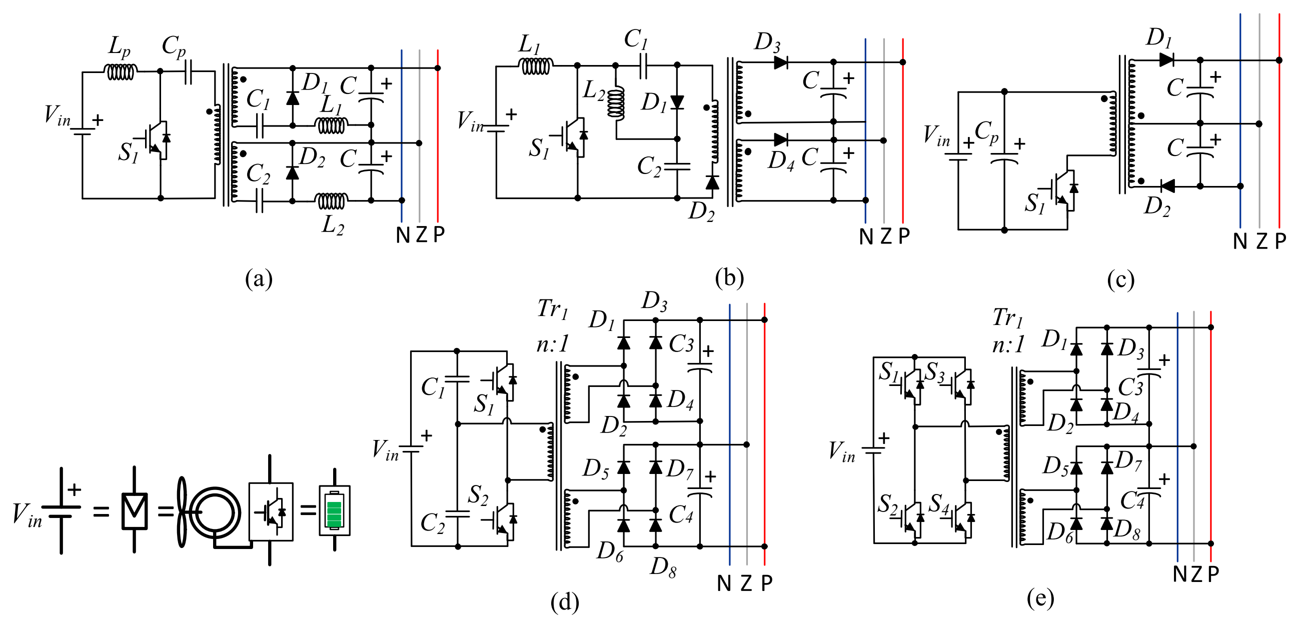

Fig. 12. Topologies with galvanic isolation for bipolar connection in generators. (a) Dual output *Ćuk* converter. (b) *SEPIC* with a flyback converter. (c) Dual output flyback converter. (d) Dual output with a half-bridge converter. (e) Dual output with a full-bridge converter.

number of passive elements is disclosed in [64]. Its schematic is drawn in Fig. 12 (c). These three solutions are characterized by the use of a single switch. Alternatives with multiples switches are composed by the half-bridge [65] or the full-bridge structures [66]. These power converters are drawn in Figures 12 (d) and 12 (e) respectively.

3) Storage systems with bipolar connection

The integration of ESSs can be also strategically planned to provide voltage balancing in the bipolar dc microgrid by means of a proper converter. Roughly, these topologies must be designed and controlled to allow bidirectional functions, allowing charging or discharging operation modes. Some cases are distinguished in Fig. 13 and explained as follows. If the voltage of the positive pole is lower than the absolute value of the negative microgrid pole, then in charging mode the energy must be injected by the negative pole and injected to the positive one in discharging mode (Fig. 13 (a)). In the opposite imbalance, the power flow will be as indicated in Fig. 13 (b). Then, when dc microgrid is balanced, the energy will flow

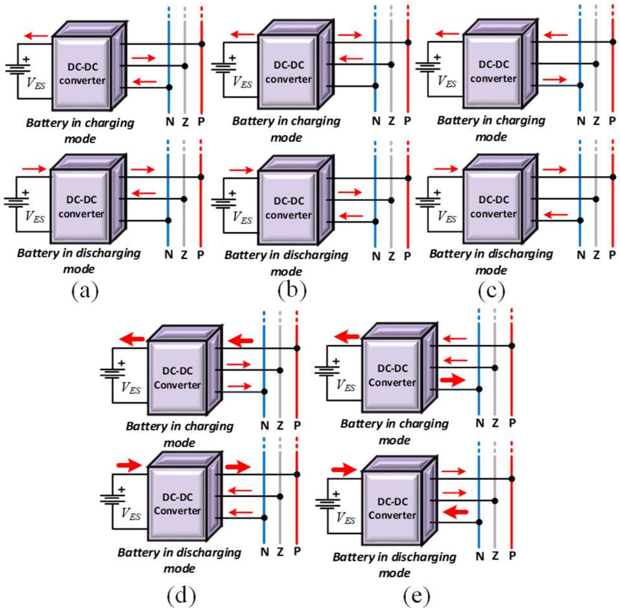

Fig. 13. Possibilities for the energy transfer between the ESS and the microgrid. (a) Lower voltage in positive pole during charging or discharging. (b) Lower voltage in negative pole. (c) Balanced operation. (d) Unbalanced operation with higher voltage in positive pole. (e) Unbalanced operation with higher voltage in negative pole.

from/to both poles (Fig. 13 (c)). In a similar way than in a generator with bipolar connection, the dc-dc converter must transfer energy to the poles asymmetrically if the ESS has enough power capability to ensure the balance of the dc microgrid. In the last subfigures 13 (d) and 13 (e), two unbalanced ways depending on which pole has a higher voltage for a charging and discharging modes of the ESS are illustrated.In this scenario there have been some proposals and possible solutions. One approach is to merge two bidirectional converters, for example, the interleaved boost-*SEPIC* converter represented in Fig. 14 (a) [67]. The input sides of both converters are connected in parallel (interleaved) and their outputs in series. The input power source can be a RES (as PVs) or ESS (as a battery), with reduced input voltage range variation. This converter was selected for interfacing with the PZ voltage (higher voltage) and ZN voltage (lower voltage). At the same time, it is possible to transfer energy from the ESS to PZ pole (switching S_4 and S_2 as a boost converter) and to the ZN pole (switching the power switch S_3 as a *SEPIC* converter). Finally, by controlling S_1 or S_2, the power flows from the dc buses into the ESS. Please note that this solution also features ZVS operation, hence efficiency is enhanced. Alternatively, the modified SC dc-dc converter can also serve not only a voltage balancer, but also as a bidirectional dc-dc converter [68]. The proposed scheme in Fig. 14 (b) can compensate unbalanced power with bidirectional power flow. These last features make this converter to be a suitable option in fast chargers or ESS interfaces in EV charging station. The energy flow from the ESS to the output capacitors (C_1 and C_2) is done by the power switches S_3 and S_4. The opposite power flow by means of S_1 and S_2. Alternatively, the three-level bidirectional dc-dc converter can be also used as ESS interface with bipolar dc microgrid. Fig. 14 (c) shows the three-level buck-boost topology used to

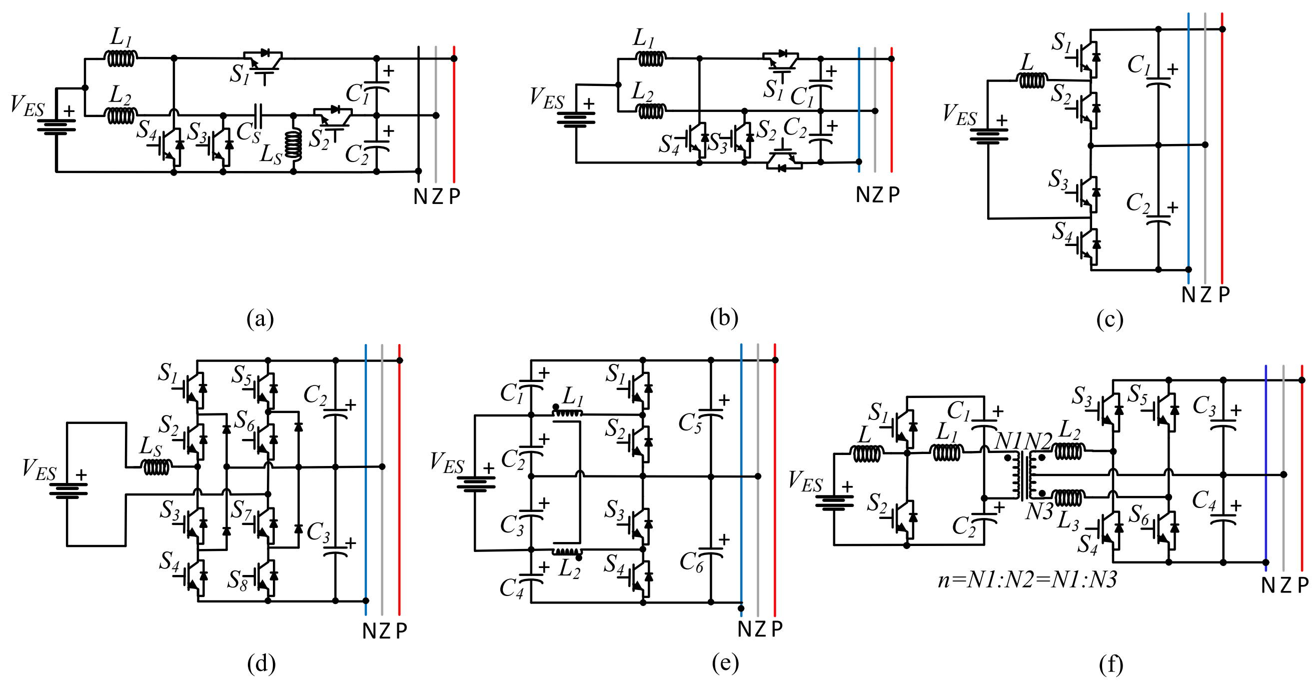

Fig. 14. Topologies for bipolar connection in ESSs. (a) Interleaved bidirectional boost-*SEPIC* voltage balancer. (b) Bidirectional modified SC-type voltage balancer converter. (c) Three-level bidirectional buck-boost type. (d) Bidirectional full-bridge three-level buck-boost voltage balancer. (e) Bidirectional full-bridge three-level buck-boost voltage balancer with coupled inductor. (f) Current feed isolated bidirectional dc-dc converter with voltage balance capability.

This article has been accepted for publication in IEEE Journal of Emerging and Selected Topics in Power Electronics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JESTPE.2022.3208689

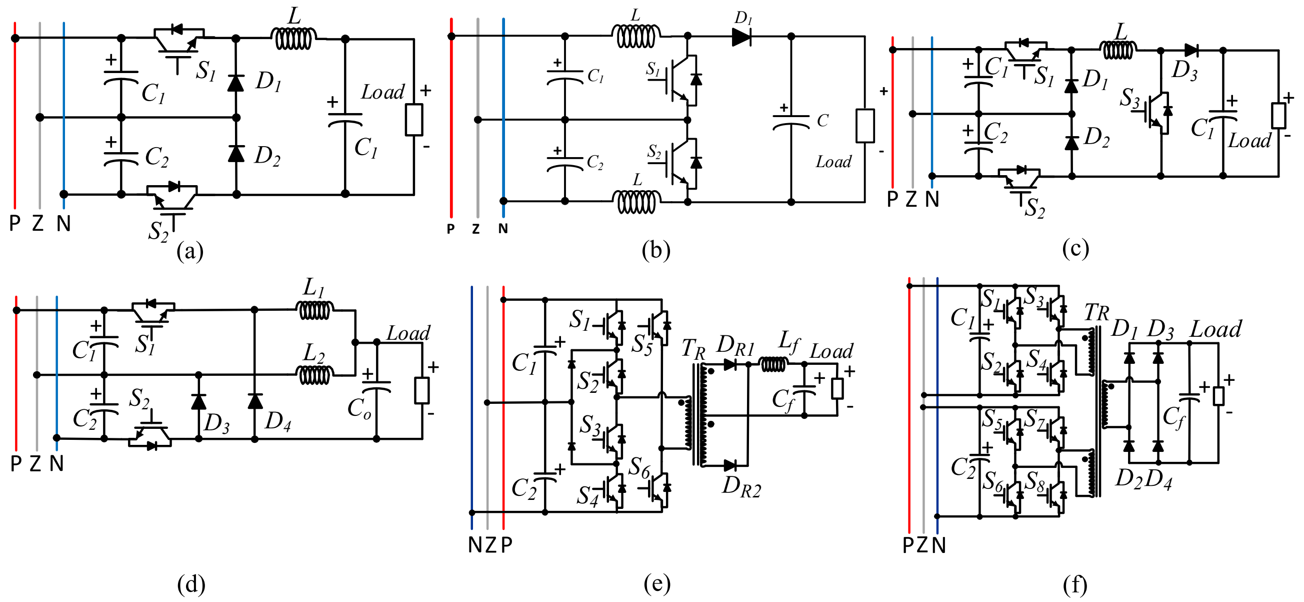

Fig. 15. Topologies for bipolar connection with loads. (a) Three-level dc-dc buck converter. (b) Three-level dc-dc boost converter. (c) Three-level dc-dc buck-boost converter. (d) Modified SC-type dc-dc converter. (e) Isolated three-level half-bridge converter. (f) Isolated two half-bridges-based converter.

support the balance of the bipolar dc microgrid with a ESS [17], [69]–[72]. The energy can be transferred from the ESS to a single or both output capacitors by combining the switching of S_2 and S_3 in boost mode. Similarly, the power flow from the capacitors to the battery is performed in buck mode with power devices S_1 and S_4. A similar three-level configuration with bipolar dc connection is presented in Fig. 14 (d) with the same capabilities. This configuration has a higher number of power devices, and allows to connect different polarities regarding the ESS. The charge or discharge of ESS and output capacitors can be done in different ways, depending on the power devices involved [73]. In that work, it is also proposed an advanced modulation strategy to minimize the current ripple during unbalanced conditions. On the other hand, [74] discloses two-half bridges with coupled inductors conforming a new bidirectional three-level dc-dc converter (see Fig. 14 (e)). It operates as two independent buck converters during normal operation (with S_1 and S_4 connected at the same time) or boost converters (using S_2 and S_3). If there is a phase-shift between S_1 and S_4 as well as S_2 and S_3, then the current flow builds up through the coupled inductor in order to transfer power between the two buses. The switches of both phases have the same duty cycle, which are regulated with a current closed-loop control. Finally, the current-fed isolated bidirectional dc-dc converter, displayed in Fig. 14 (f) has voltage balance capability interfacing with ESS [75], [76]. The low-voltage side input inductor and the switch leg (S_1 and S_2) constitute a bidirectional buck-boost dc-dc converter. Controlling those power switches and S_5 and S_6 in the high side the energy in transferred from the ESS to the output capacitors C_3 and C_4, balancing at the same time. This topology presents a wide input voltage range and low input current ripple with almost ZVS during the whole operating range. DAB based solutions with high-efficient performance are also proposed [77], [78].

4) Loads with bipolar connection

The last option for supporting the voltage balance is performed through the load connection [79]. There are three ways to transfer the energy depending on the type of imbalance. The power is transferred by the positive pole, by the negative pole or by both depending on the instantaneous voltage levels in each dc bus. The most common circuits found for these applications are based on three-level structures, selecting which bus must be used to supply power to the load. It is important to note that if this circuit is not necessarily used to supply desired equipment, then this solution is very disadvantageous since it involves a dissipative process. Due to this reason, only a few topologies with connected loads have been proposed to be used in the bipolar microgrid with the objective of supporting the voltage balance of the networks. For example, Figures 15 (a), 15 (b) and 15 (c) shows three different three-level topologies with different voltage gain characteristics, namely buck, boost and buck-boost connected with loads while providing voltage support [57], [80]. The modified SC dc converter ([47], [68]) represented in the 15 (d) may also transfer energy from the positive or from the negative pole to the load by using S_1, D_3 and D_4 or S_2 and D_3 respectively. The transfer from both buses is achieved combining S_1, S_2, D_3 and D_4. Finally, some solutions of dc-dc converters with galvanic isolation have also been proposed for this purpose. An isolated topology is derived from the three-level buck converter [57]. Furthermore, the combination of two full-bridges are connected to the positive and negative poles feeding a load. These converters are schematized in the figures 15 (e) and 15 (f) respectively.

IV. Overall Comparison and Discussion

This section aims to provide an insightful summary of each type of solution analyzed for providing the support to the bipolar dc microgrid. The structure and classification follow the same scheme presented in Fig. 4. For comparison purposes, it was considered several characteristics of the topologies, such as, voltage gain by each output, number of power semiconductors, number of passive components and shoot-through problems. Another aspect that was also considered was a parameter that takes into consideration all the power semiconductors. In this way, it was considered the total blocking voltage, although other parameters, such as, the total component stress factor, among others alike, can also be used [81-84]. These characteristics can be a decisive factor for the researcher/engineers to select one of them in a particular application.

A. Centralized Architecture

Table II and Table III presents a comprehensive comparison considering the previous features. It is possible to derive that all the topologies provide the buck-boost operation modes, but they usually perform this operation separately in centralized voltage balancers. Since the control strategy relies usually on energy transfer from the bus with higher voltage to the bus with lower voltage, then the buck mode is normally adopted. Nevertheless, the boost mode can also be used if necessary. Additionally, the topologies number five and six can provide buck-boost operation with different voltage gain depending on the energy transfer requirements. In general, non-isolated topologies require less switches, but suffer from a higher voltage stress. Isolated topologies require a higher number of switches but allow a higher voltage gain.

TABLE II
Centralized Topologies Summary

Top.	Designation	Figure and reference	Classification
1	Buck-boost type	Fig. 6 (a), [15, 20, 28]	Non-isolated multiple switch topologies
2	Improved buck-boost converter	Fig. 6 (b), [29]	
3	Dual buck-boost converter	Fig. 6 (c), [30]	
4	Based on *Ćuk* converter	Fig. 6 (d), [20, 28]	
5	Based on bidirectional *Super-SEPIC*	Fig. 6 (e) [28]	
6	bidirectional *Super-Zeta*	Fig. 6 (f) [28]	
7	Interleaved buck-boost	Fig. 6 (g) [20, 28]	
8	Based on three-level buck-boost converter	Fig. 6 (h) [20, 28, 34]	
9	NPC converter with a three-level	Fig. 6 (i) [17]	
10	Three-level dual buck-boost	Fig. 6 (j) [34]	
11	Based on DAB with two stages	Fig. 7 (a) [38]	Isolated multiple switch topologies
12	Based on DAB with one stage	Fig. 7 (b) [38]	
13	Based on two-level DAB	Fig. 7 (c) [40]	
14	Three-level DAB	Fig. 7 (d) [41]	
15	Isolated dc–dc converter with buck–boost VB Three-level DAB	Fig. 7 (e) [40]	
16	Dual-active-half-bridge with LC voltage balancer	Fig. 7 (f) [40]	

B. Decentralized Architecture

According to the Fig. 4, these solutions were listed into standalone voltage balancer, which requires an extra dc-dc converter, and the use of specific converter for generators, ESS and loads for injecting or demanding power in balanced or unbalanced way into/from the bipolar dc microgrid.

Table IV include the general summary of the solutions adopted as standalone voltage balancers. At the same time, table V collects the main parameters and factors considered for the comparison. Despite some topologies can perform buck and boost actions, they usually work only in buck mode as the control strategy relies on the energy transfer from the bus with higher voltage to the bus with lower voltage. As main conclusion, the topology presented in the Fig. 8 (a) requires less switches and passive components. On the other hand, the topology shown in the Fig. 8 (b) requires switches with lower voltage stress.

The summary table with the main features of solutions to connect generators with voltage balancing capability are presented in the Tables VI and VII. The topologies with boost operation requires switches with lower voltage stress and a smaller number of passive components, however, they do not allow to operate in buck mode, which can be a limitation to their applications. If the operation of the generator with the microgrid requires a high voltage operation gain, then the topologies with transformers are recommended. These solutions allow a lower voltage rated switches.

Tables VIII and IX sum up the special converters proposed for the interconnection between ESSs and a bipolar dc microgrid. The circuit depicted in Fig. 14 (b) performs both buck and boost operation and requires fewer passive components and lower voltage stress over switches. The isolated topology only provides buck operation, but it is possible to match the ESS voltage with the dc bus voltage by choosing an appropriate number of turns for the transformer windings.

Finally, the reviewed topologies that can be used to connect loads and providing voltage support simultaneously in the bipolar dc microgrid are summarized in Tables X and XI. The solution with a wider voltage operation range is the topology based on buck-boost, however, it requires more components if compared to other non-isolated topologies.

V. Conclusions

As depicted in the paper, bipolar dc grids hold the potential play a critical role to support the modernization of the electric grid. Their inherent flexibility, enhanced efficiency and

TABLE III
CENTRALIZED TOPOLOGIES CHARACTERISTICS (1-8)

Charact.	**Topology**							
	1	2	3	4	5	6	7	8
Total Blocking voltage	$2V_0$	$V_{in}+V_0$	$2V_{in}+2V_0$	$2V_0$	V_0	V_0	$4V_0$	$3V_0$
Voltage gain by each output	D (*) $\frac{1}{1-D}$ (#)	D (*) $\frac{1}{1-D}$ (#)	D (*) $\frac{1}{1-D}$ (#)	$\frac{1}{1-D}$	$\frac{D_1}{2D_1-1}$; $(D_1 < 0.5)$(£) $\frac{1-2D_2}{1-D_2}$; $(D_2 > 0.5)$(§)	$\frac{D_1}{2D_1-1}$; $(D_1 < 0.5)$(£) $\frac{1-2D_2}{1-D_2}$; $(D_2 > 0.5)$(§)	D (*) $\frac{1}{1-D}$ (#)	D (*) $\frac{1}{1-D}$ (#)
Number of switches	2	3	2	2	2	2	4	4
Number of diodes	0	0	2	0	0	0	0	2
Number of inductors	1	2	2	2	2	2	2	1
Number of capacitors	0	0	0	1	1	1	0	0
ST Problem for the output	yes	yes	no	no	no	no	yes	yes
Transformer	no	no	no	no	no	no	no	no

ST – Shoot -Through; n – turns ratio of the transformer; (*) – Buck operation; (#) – Boost operation; (£) – Transfer energy from PZ to ZN; (§) – Transfer energy from ZN to PZ.

TABLE III
CENTRALIZED TOPOLOGIES CHARACTERISTICS (9-16) CONTINUATION

Characteristics	**Topology**							
	9	10	11	12	13	14	15	16
Total Blocking voltage	$12V_0$	$5V_0$	$4V_{in}+8V_0$	$4V_{in}+4V_0$	$4V_{in}+4V_0$	$3V_{in}+6V_0$	$2V_{in}+4V_0$	$2V_{in}+2V_0$
Voltage gain by each output	D (*) $\frac{1}{1-D}$ (#)	D (*) $\frac{1}{1-D}$ (#)	nD (*) $\frac{n}{1-D}$ (#)	nD (*) $\frac{n}{1-D}$ (#)	nD (*) $\frac{n}{1-D}$ (#)	nD (*) $\frac{n}{1-D}$ (#)	nD (*) $\frac{n}{1-D}$ (#)	nD (*) $\frac{n}{1-D}$ (#)
Number of switches	16	4	12	8	12	12	6	4
Number of diodes	8	4	0	0	0	6	0	0
Number of inductors	1	2	3	3	3	1	2	2
Number of capacitors	0	0	2	1	1	2	2	2
ST Problem for the output	yes	no	yes	yes	yes	yes	yes	yes
Transformer	no	no	yes	yes	yes	yes	yes	yes

ST – Shoot -Through; n – turns ratio of the transformer; (*) – Buck operation; (#) – Boost operation.

availability make them ideal for emerging high-performance applications such as EV charging infrastructure, modern data centers or LVDC distribution systems in buildings. Despite being prone to issues with voltage imbalances and asymmetries, the availability of a wide variety of balancing power converters permits to guarantee stable bipolar grids, while meeting the requirements of different applications. This paper covers the origin of these issues, illustrating the different scenarios that could lead to asymmetries in bipolar grids in order to clearly explain the ways to address them. Additionally, the study

TABLE IV
STANDALONE TOPOLOGIES SUMMARY

Top.	**Designation**	**Figure and reference**	**Classification**
17	Buck-boost converter	Fig. 8 (a), [46]	Non-isolated multiple switch topologies
18	Modified SC converter	Fig. 8 (b), [47]	
19	Current redistributor	Fig. 8 (c), [29], [48]	

TABLE V
STANDALONE CHARACTERISTICS

Characteristics	**Topology**		
	17	18	19
Total Blocking voltage	$2V_0$	$\frac{5V_0}{2}$	$6V_0$
Voltage gain by each output	D (*) $\frac{1}{1-D}$ (#)	D (*) $\frac{1}{1-D}$ (#)	D
Number of switches	2	4	6
Number of diodes	0	0	0
Number of inductors	1	2	3
Number of capacitors	0	0	0
ST Problem for the output	yes	no	yes
Transformer	no	no	no

TABLE VI

TOPOLOGIES SUMMARY USED WITH GENERATORS

Top.	Designation	Figure and reference	Classification
20	Based on *Ćuk -SEPIC*	Fig. 10 (a) [49]	Non-isolated single switch topologies
21	Based on *Ćuk -SEPIC* converter with integrated magnetic cores	Fig. 10 (b) [50]	
22	Buck-boost-*Zeta* converter	Fig. 10 (c) [51], [52]	
23	Based on voltage lift technique with double-output converter	Fig. 10 (d) [53]	
24	Boost with self-lift converter	Fig. 10 (e) [54], [55]	
25	Quasi-Z with self-lift converter	Fig. 10 (f) [56]	
26	Based on three-level boost converter	Fig. 11 (a) [57]	Non-isolated multiple switch topologies
27	Based on three-level buck-boost converter	Fig. 11 (b) [57]	
28	Based on three-level *SEPIC* converter	Fig. 11 (c) [57]	
29	Input-parallel output-series DC-DC boost converter	Fig. 11 (d) [58], [59]	
30	Boost- *Zeta* converter	Fig. 11 (e) [58]	
31	Based on *Ćuk -SEPIC* converter	Fig. 11 (f) [58]	
32	Three-level quadratic Boost converter	Fig. 11 (g) [60]	
33	Two-phases interleaved *Ćuk -SEPIC* converter	Fig. 11 (h) [61]	
34	Dual output *Ćuk* converter	Fig. 12 (a) [62]	Isolated multiple switch topologies
35	*SEPIC* with a flyback converter	Fig. 12 (b) [63]	
36	Dual output flyback converter	Fig. 12 (c) [64]	
37	Dual output with a half-bridge converter	Fig. 12 (d) [65]	
38	Dual output with a full bridge converter	Fig. 12 (e) [66]	

TABLE VII

TOPOLOGIES CHARACTERISTICS USED WITH GENERATORS (20-29)

Characteristics	Topology									
	20	21	22	23	24	25	26	27	28	29
Total Blocking voltage	$V_{in}+V_o$	$V_{in}+V_o$	$V_{in}+V_o$	$V_{in}+2V_o$	$2V_{in}$	$V_{in}+2V_o$	$4V_{in}-2V_o$	$5V_{in}-2V_o$	$4V_{in}-2V_o$	$4V_{in}-\frac{3}{2}V_o$
Voltage gain by each output	$\frac{D}{1-D}$	$\frac{D}{1-D}$	$\frac{D}{1-D}$	$\frac{1}{1-D}$	$\frac{1}{1-D}$	$\frac{2}{1-2D}$	$\frac{1}{2(1-D)}$	$\frac{D}{2(1-D)}$	$\frac{D}{2(1-D)}$	$\frac{1}{1-D}$
Number of switches	1	1	1	1	1	1	2	2	2	2
Number of diodes	2	2	2	4	3	4	2	4	2	3
Number of inductors	4	3	2	3	1	2	1	1	2	2
Number of capacitors	4	4	3	6	3	4	2	2	4	3
ST Problems	no	no	no	no	no	no	yes	no	yes	yes
Transformer	no	no	no	no	no	no	no	no	no	no

ST – Shoot-Through.

TABLE VII

TOPOLOGIES CHARACTERISTICS WITH GENERATORS (30-38) (CONTINUATION)

Characteristics	Topology								
	30	31	32	33	34	35	36	37	38
Total Blocking voltage	$2V_{in}-\frac{1}{2}V_o$	$V_{in}+V_o$	$2V_o$	$2V_{in}-V_o$	$V_{in}+V_o$	$2V_{in}+V_o$	$V_{in}+V_o$	$2V_{in}+4V_o$	$4V_{in}+4V_o$
Voltage gain by each output	$\frac{D}{1-D}$	$\frac{D}{1-D}$	$\frac{1}{2(1-D)^2}$	$\frac{D}{1-D}$	$\frac{nD}{1-D}$	$\frac{nD}{1-D}$	$\frac{nD}{1-D}$	$\frac{nD}{2}$	nD
Number of switches	2	2	2	$1k$	1	1	1	2	4
Number of diodes	2	2	4	$2k$	2	4	4	8	8
Number of inductors	3	4	2	$4k$	3	2	-	-	-
Number of capacitors	3	4	3	$4k$	5	4	3	4	3
ST Problems	no	no	no	no	no	no	no	yes	yes
Transformer	no	no	no	no	yes	yes	yes	yes	yes

ST – Shoot-Through; n – turns ratio of the transformer; k – number of interleaved phases.

provides an exhaustive survey of the existing dc-dc converters that enable voltage balancing in bipolar grids, discussing their structure, power circuits and how the redistribution or relocation of power is performed. More importantly, the article compares the existing options from different perspectives: centralized or decentralized architectures, balancers interacting with generators, loads or ESSs, isolated or transformer-less converters, and standalone or distributed solutions. These comparisons are summarized in tables along with discussions based on their advantages and limitations, thereby helping

This article has been accepted for publication in IEEE Journal of Emerging and Selected Topics in Power Electronics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JESTPE.2022.3208689

TABLE VIII
TOPOLOGIES SUMMARY WITH ESS

Top.	Designation	Figure and reference	Classification
39	Interleaved *SEPIC* converter	Fig. 14 (a), [67]	Non-isolated single switch topologies
40	Bidirectional SC-type converter	Fig. 14 (b), [68]	
41	Based on three-level buck-boost converter	Fig. 14 (c), [17],[69]–[72]	
42	Based on three-level full-bridge buck-boost	Fig. 14 (d), [73]	
43	Based on three-level buck-boost converter with coupled inductors	Fig. 14 (e) [74]	
44	Current fed isolated converter	Fig. 14 (f) [75], [76]	Isolated multiple switch topologies

TABLE IX
TOPOLOGIES CHARACTERISTICS WITH ESS

Characteristics	Topology					
	39	40	41	42	43	44
Total Blocking voltage	$4V_{in} - 2V_o$	$4V_{in} - 2V_o$	$2V_o$	$6V_o$	$2V_o$	$2V_{in} + 4V_o$
Voltage gain by each output	$\frac{D_1}{1-D_1}(*)$ $\frac{1}{1-D_2}(\#)$	$\frac{D}{1-D}$	$\frac{D}{1-D}$	$\frac{D}{1-D}$	$\frac{D}{1-D}$	nD
Number of switches	4	4	4	8	4	6
Number of diodes	0	0	0	4	0	0
Number of inductors	3	2	1	1	2	4
Number of capacitors	1	0	0	0	4	3
ST Problems	yes	yes	yes	yes	yes	yes
Transformer	no	no	no	no	no	yes

ST – Shoot-Through; n – turns ratio of the transformer. (*) – to ZN output voltage (*SEPIC*); # – to PN output voltage (boost).

readers to develop new ideas or orient their designs by identifying the most suitable approach to guarantee the regulation of bipolar grids. The latter can be a decisive factor for researcher/engineers to select the structure for a particular application.

TABLE X
TOPOLOGIES SUMMARY USED WITH LOADS

Top.	Designation	Figure and reference	Classification
45	Buck converter	Fig. 15 (a), [57], [80]	Non-isolated single switch topologies
46	Boost converter	Fig. 15 (b), [57], [80]	
47	Buck-boost converter	Fig. 15 (c), [57], [80]	
48	Modified SC	Fig. 15 (d), [45], [68]	
49	Based on three-level half-bridge buck converter	Fig. 15 (e) [57]	
50	Based on three-level full-bridge buck converter	Fig. 15 (f) [57]	Isolated multiple switch topologies

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TABLE XI
TOPOLOGIES CHARACTERISTICS USED WITH LOADS

Characteristics	Topology					
	45	46	47	48	49	50
Total Blocking voltage	$2V_o$	$2V_o$	$3V_o$	$\frac{5V_o}{2}$	$4V_o + nV_o$	$4V_o + 2nV_o$
Voltage gain by each output	D	$\frac{1}{1-D}$	$\frac{D}{1-D}$	D	nD	nD
Number of switches	2	2	3	2	6	8
Number of diodes	2	1	3	2	2	4
Number of inductors	1	2	1	2	1	1
Number of capacitors	1	1	1	1	1	1
ST Problems	no	no	no	no	yes	yes
Transformer	no	no	no	no	yes	yes

ST – Shoot-Through; n – turns ratio of the transformer.

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