A technical overview of single-stage three-port dc-dc-ac converters

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Keywords

≪DC-AC converters≫, ≪Double-input converter≫, ≪Hybrid power integration≫,
≪Emerging technology≫, ≪Split-Source inverter≫.

Abstract

Multiport dc-ac converters are becoming a pivotal technology to integrate renewable energy sources, energy storage systems and ac grids/loads. This article presents a classification and comparative analysis of the recently proposed single-stage three-port topologies. The study leads to the definition of three major groups, based on the operation principle to perform the dc-dc-ac power conversion. Each group is analysed in terms of the rated power, voltage boost characteristic and components count. Furthermore, a comparative study is performed to provide the best suited applications for each category.

Introduction

Hybrid power systems integrating renewable energy sources (RES), energy storage systems (ESS) and ac grids/loads have risen rapidly in the later years. In this context, systems with two dc elements connected to an ac port have become relevant because of their multiple applications, such as photovoltaic systems with integrated ES and hybrid EV powertrains [1,2]. Therefore, there is a growing interest in developing multi-functional three-port power conversion systems with high power density and efficiency [3]. Thus, single-stage three-port topologies have been proposed due to their reduction of power processing stages and required components. These topologies perform the tasks of two or three separated converters, allowing the power flow control between three sources/loads with an optimised power processing stage. Reference [4] presents a throughout analysis of three-port dc-dc converters focused on PV-ESS applications and concludes that the extension to three-port dc-dc-ac converters is an essential topic to further investigations.

Single-stage three-port dc-dc-ac power converters have emerged during the last decade, looking to interface the elements of different hybrid power systems. The motivation behind these topologies is to reduce the required components, thus improving the efficiency and reliability of the power conversion system [5]. Additionally, they can provide extra features as embedded boost capabilities, continuous current at the dc elements or galvanic isolation with the ac port [6, 7]. However, they also present some limitations, as restricted power regulation capabilities and the need for advanced control and modulation techniques. Nevertheless, better-suited topologies for different applications can be determined, considering the mentioned limitations at the design stage. Thus, a comparative analysis of these single-stage three-port topologies is fundamental to classify them according to their features and possible applications.

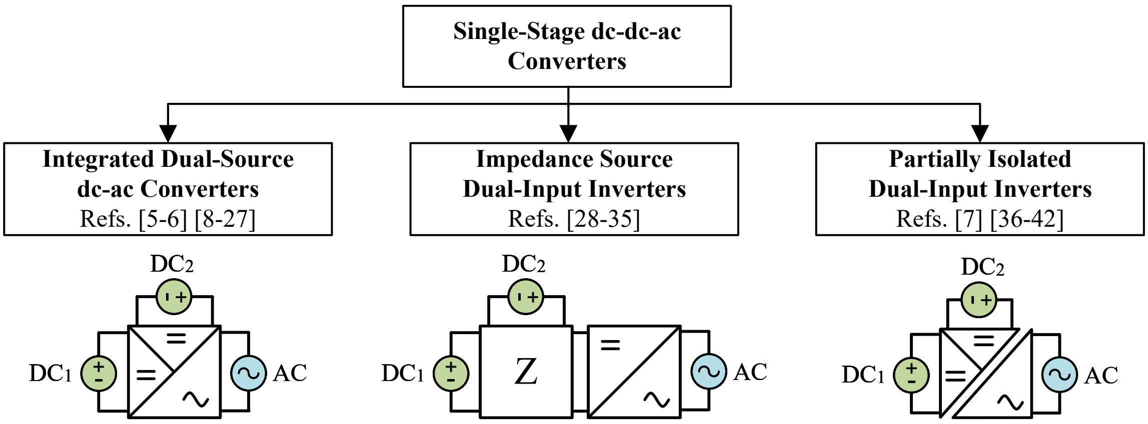


Fig. 1: Classification of single-stage three-port dc-dc-ac converters

This paper will present a technical overview of the single-stage three-port dc-dc-ac converters proposed for emerging hybrid power systems. The objective is to introduce a comparative analysis between the different converters based on the topology characteristics, features, limitations and applications. The study also classifies the different topologies based on the operating principle used to minimise the power processing stages. The latter looks for standardising the existing solutions to facilitate the state-of-art analysis for future proposals. The following sections present the proposed classification for the single-stage three-port dc-dc-ac converters, the relevant application cases and a comparative study considering the features of the analysed the topologies.

Topologies classification

Fig. 1 presents the proposed classification for the single-stage three-port dc-dc-ac topologies published in the last decade. Three major groups are defined based on the topology feature allowing the connection of the two dc ports with the ac side. This section will present a description of the proposed categories, with focus on the topologies and operation principles.

Integrated dual-source dc-ac converters

The first category is called integrated dual-source dc-ac converters, it contains three-port topologies that use as a basis a conventional dc-ac converter. Fig. 2 shows the overall topology of these solutions for a single-phase case, although they also work in three-phase systems. The topologies in this category integrates a dc-dc conversion within the legs of the conventional dc-ac converter, thus enabling the power flow with the second dc port. The interface connecting the second dc port allows to define three major groups within this category.

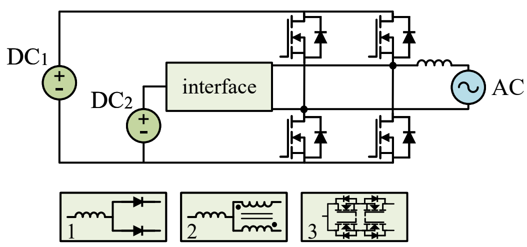


Fig. 2: Integrated dual-source dc-ac converter examples

The first subcategory (Fig. 2, interface 1) correspond to the split-source inverters [8–17], which embed a boost stage on one or more legs of the dc-ac converter. These topologies allows to transfer power from a low voltage dc source to both dc_1 and ac ports, using the legs of the converter to control two currents at the same time (L_{dc2}, L_{ac}). This is possible due to a degree of freedom (DoF) given by the switching states of the converter, as the zero states for the ac side (both upper or lower switches activated) create a different path for the current of L_{dc2}. Thus, a multi-variable control to enable the power regulation between the three ports is performed using modified modulation schemes. The minimum additional components to generate this topology are one dc inductor and one diode per leg, thus the components count is reduced compared to a classical two-stage implementation. The use of diodes limits the power flow to be unidirectional from port dc_2, and also exposes these diodes to the fast switching of the converter legs.

The second subcategory (Fig. 2, interface 2) include the buck-boost three-port converters (TPC) [6, 18–21] that integrate a buck-boost conversion to each leg of the dc-ac converter. These topologies have similar features to the split-source subcategory, but they add bidirectional power flow between all three ports. Topology in [6] uses one inductor per leg, enabling the simultaneous operation as a dc-ac converter between dc_1 and ac ports and as interleaved buck-boost converter between dc_1 and dc_2. The operation is also based in a multi-variable controller exploiting the DoF available to regulate the power flow between the sources and loads of the system. The minimum additional components for the operation of this topology is one inductor per leg, eliminating the need for extra semiconductor devices for the connection of the second dc port. Although current at port dc_2 is purely dc, the inductors' currents include an ac component at the frequency of the ac port. Therefore, the size of these passive components increase for low frequency applications. However, including magnetic coupling between the windings reduces the resultant ac flux and consequently the required size of these components.

The last subcategory (Fig. 2, interface 3) consists on the dual-port asymmetrical multilevel converters (DP-AMI) [5, 22–27], which use modified three-level converters connecting the second dc port to the neutral point. Thus, these converters (NPC or T-type) replace the connection to the mid-point of dc_1 port by a connection to the new dc_2 element. This group also uses the DoF given by the switching states of the topologies to perform bidirectional power flow between the three ports. Furthermore, the operation is more flexible due to the increased number of states given by the additional semiconductor devices. These topologies use at least twice the number of switching devices compared to the first two subcategories, but there is no need for extra passive components. The main limitation of this group is the limited power regulation capability for port dc_2, which leads to the use of an auxiliary dc-dc converter to extend this operation range. This limitation is generated by the unbalanced operation of the three-level converters and it varies with the voltage ratio between both dc ports.

Table I shows the components comparison for three examples of the subcategories described in the present subsection. The split-source inverter shows the higher voltage boost capability for port dc_2, reaching maximum gain values of 4 to 5 [10]. However, the modulation scheme should be carefully selected to minimise low-frequency ac ripple at the current of this second dc port that can be detrimental for batteries or fuel-cells. The buck-boost three-port converter presents the most flexible power range, as the power flow for port dc_2 is symmetrical for both source and sink scenarios. The current at dc_2 is free of low-frequency oscillations due to the interleaved operation of the interface inductors. Nevertheless, these inductors will have ac components at the frequency of the ac port, leading to higher volume and losses. The latter can be addressed at the design stage by including magnetic coupling to reduce the ac component currents on the windings. Finally, the dual-port AMI shows the best power quality at the ac side, due to the increase number of available switching states. Additionally, the volume is reduced as there is no need for extra passive components. However, the power regulation capability is reduced at port dc_2, complicating its use with elements that require wide bidirectional power flow capabilities as batteries or supercapacitors.

Table I: Summary for three-phase implementations of integrated dual-source dc-ac converters

Reference	Topology	Transistors	Diodes	Inductors	Power flow
[8]	Split-source inverter	6	3	1	Unidirectional
[6]	Buck-boost TPC	6	0	3	Bidirectional
[25]	Dual-port AMI	12	0	0	Bidirectional

Impedance source dual-input inverters

The second category includes the impedance source converters modified to incorporate a second dc input on the impedance network. These topologies use one of the available capacitors in the Z- or qZ-source network to connect a dc element exchanging power with both dc input and ac output. Fig. 3 shows the overall structure of these converters for a single-phase configuration, which can be extended to a three-phase. These converters work actuating on two control inputs: the modulation index of the dc-ac converter and the shoot-through ratio that allows boosting the voltage of the dc ports. Therefore, these two DoF are used to regulate the currents at the ac and one of the dc ports, using the remaining one to address the power balance between the three elements.

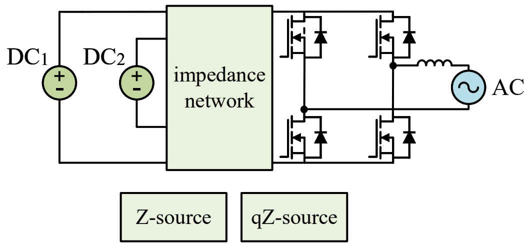


Fig. 3: Impedance source dual-input inverter examples

The Z-source inverter [28] includes a second dc source in one of the capacitors of the impedance network, allowing bidirectional power flow between all three ports. Additionally, it can provide boost capabilities using the shoot-through state of the dc-ac converter. However, the boost ratio should be kept between 1 to 2 as higher values generate excessive losses. References [29, 30] use two impedance networks and coupled inductors to enhance the boost capabilities, but at expenses of doubling the amount of required passive elements. The main limitation of the Z-source inverters is the discontinuous current at the dc elements, which has to be addressed by large size input capacitors.

The second type of converters in this category correspond to the quasi-Z-source inverters, which uses a modified impedance network creating a common dc rail between dc_1 and *ac* ports [31–35]. This topology follows the same operational principle of the Z-source, but features continuous dc currents at both ports and consequently reduce passive components sizing. The reported qZ-source converters provide limited voltage boost capabilities by using both dc ports with the impedance network to generate a higher voltage at the *ac* port.

Table II presents the components comparison for three examples of converters in this category. The switching devices count is kept low, as the needed DoF is given by the impedance network itself (with the shoot-through state). Voltage boost capability can be achieve with a dual impedance network, but the passive components count is significantly incremented. The qZ-source inverter shows the best operative conditions for the dc elements, and it is the most adequate choice when there is no requirement for a high-ratio voltage boost.

Table II: Summary for three-phase implementations of impedance source dual-input dc-ac converters

Reference	Topology	Transistors	Diodes	Inductors	Capacitors	Voltage Boost
[28]	Z-source	7	0	2	2	Limited
[29]	Z-source	7	4	2*	8	High
[31]	qZ-source	6	1	2	2	Limited

**Inductors are replaced with three-winding transformers in this case.*

Partially isolated dual-input inverters

The last category consists of the partially isolated dual-input inverters, which feature galvanic isolation between the dc ports with the ac side (Fig. 4). These converters are based on microinverter topologies, as the Flyback [36–39] and the dual active bridge (DAB) [7, 40–42], including an extra dc port on the primary side of the transformer. Additionally, they use a current source converter on the secondary to interface directly the high-frequency signals with the low-frequency grid. Therefore, these converters manage to connect the three ports without requiring extra unfolding or power conditioning stages. Modulation techniques as the dual-phase shift or triple-phase shift give the DOFs required to control the power flow between the elements. Furthermore, partially isolated dual-input converters have embedded voltage boost capabilities with the transformer. Also, some of them can work with soft-switching increasing the overall efficiency of the solution.

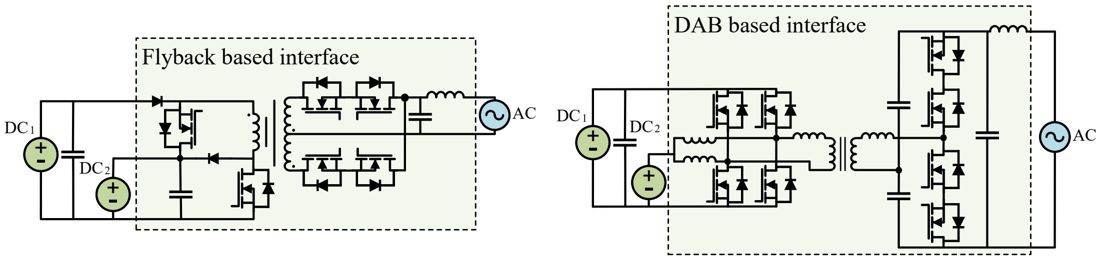


Fig. 4: Partially isolated dual-input inverter examples

These converters have a reduced volume due to the use of a high-frequency link that decreases the sizing of the required passive components. Therefore, they are suitable for its use as PV microinverters with energy storage support, enhancing the overall operation of the system. The main limitaion for this category is the elevated number of components and the complexity of the control and modulation techniques, compared to the previous categories.

Applications

Three-port dc-dc-ac converters present features that enable their use in different applications relevant for the present and future electrical system. Among these applications, the ones that can be highly benefited with single-stage conversion systems are:

- On- and off-grid hybrid PV-BES systems
- Hybrid EV powertrains
- On-grid low voltage PV or BES with embedded boost stage
- Hybrid fuel-cell BES systems
- PV green hydrogen generation

Hybrid PV-BES systems are already commercially available, and most of the solutions use power conversion systems with two or more power processing stages. Thus, the development of single-stage three-port converters can help to improve the efficiency and reliability of the system by reducing the number of components. The same principle applies for other commercially available systems, such as dual-PV systems. Additionally, single-stage three-port converters can also connect individual low-voltage elements (PVs or BES) to the grid, using the embedded boost capabilities present in some of the described topologies.

Hybrid EV powertrains are another application field that can be benefited by using single-stage three-port converters. These systems require to manage power interactions between the vehicle battery, an auxiliary dc source, as supercapacitors or fuel-cells, and the electrical machine performing the traction. Therefore, the reduction of power conversion stages can decrease the overall losses and volume of the solution, which are critical parameters in the design of such systems. Furthermore, single-stage three-port topologies can also be beneficial for newer applications related to the use of hydrogen. For example, fuel-cell systems could enhance its operation by using a second dc energy storage element as complement. Moreover, the generation of green hydrogen using PV energy is also an interesting field to explore the use of three-port topologies in an efficient and reliable manner.

Figure 5 showcase the listed applications that can enhance its operation using single-stage three-port topologies. The integrated dual-source converters present features, such as bidirectional power flow and boost capabilities, that allow their use in several applications. Moreover, the reduced component count of these topologies can decrease the total volume and failure rate of the power conversion stage, generating a positive impact on applications such as hybrid PV-BES and new hydrogen applications. However, these topologies use the redundant switching states of the converter to regulate the power flow, generating oscillations in the common-mode voltage. Therefore, their use in hybrid EV powertrains should be further analysed, as these oscillations could be detrimental to electric motors. Impedance source dual-input converters also show bidirectional power flow and boost capabilities for the dc ports, with a reduced count of active devices. Additionally, common-mode voltage oscillations can be reduced

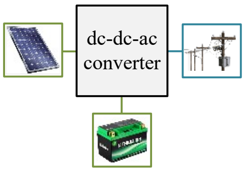
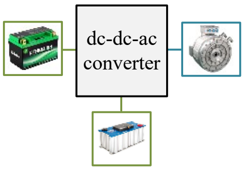
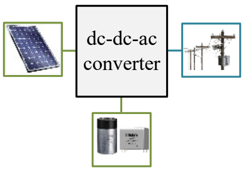
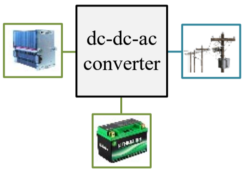
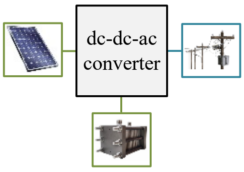
Application	Needed Features	Useful Features	Suitable Topologies
	- Bidirectional power flow at battery port. - Low-frequency ripple rejection at battery port.	- Extended power regulation capability to address variability of resource. - Boost capability to reduce serial connections PV or battery arrays.	- Buck-boost TPC & dual-port AMI. - qZ-source dual-input converter. - Partially isolated dual-input converters.
	- Bidirectional power flow for the three ports. - Low-frequency ripple rejection at battery port.	- Extended power regulation capability to address dynamic operation. - Reduced common-mode voltage variations to protect the motor.	- Z-source dual-input converter. - qZ-source dual-input converter.
	- High voltage gain.	- Extended power regulation capability to address variability of resource. - Reduced leakage currents.	- Split-source inverters. - Partially isolated dual-input converters.
	- Bidirectional power flow at battery port. - Low-frequency ripple rejection at dc ports.	- Continuous steady current at fuel-cell port. - Boost capability to connect to the ac grid.	- Buck-boost TPC & dual-port AMI. - qZ-source dual-input converter.
	- Continuous steady current at electrolyzer port. - Low-frequency ripple rejection at electrolyzer port.	- Extended power regulation capability to address variability of resource. - Boost capability to connect to the ac grid.	- Buck-boost TPC & dual-port AMI. - qZ-source dual-input converter.

Fig. 5: Three-port converter applications and key features for their operation.

through modulations techniques, enabling its use for hybrid EV powertrains. Finally, partially isolated dual-input inverters are best suited for low-power PV or hybrid PV-BES systems connected to the ac grid due to the use of high-frequency transformers. The transformer perform voltage boost and also provide galvanic isolation, maximising the impedance of the leakage current path. Furthermore, these topologies present high efficiencies as soft-switching techniques can be implemented for the active devices.

Discussion

This section present a comparative analysis based on the features of the three-port topologies previously described. The main parameters to perform the comparison are: Operation principle and control system requirements, power ratings and power flow capabilities, voltage boost capabilities and quantity of active and passive components.

The operation principle of the single-stage three-port topologies is to use the available DoFs to perform the task that normally would be carried on by a second conversion stage. Thus, the three categories condense dc-dc and dc-ac conversion functionalities into an individual power converter. The first category (Integrated dual-source) uses the redundant states of a standard dc-ac converter to control a second current at a dc port in addition to the current at the ac port. Two main control schemes have been proposed in previous literature: The first scheme uses a nested loop with single-variable controllers for each current, together with a modified modulation scheme allowing to make use of the redundant switching states; And the second scheme uses a multi-variable controller acting directly on the switching states based on

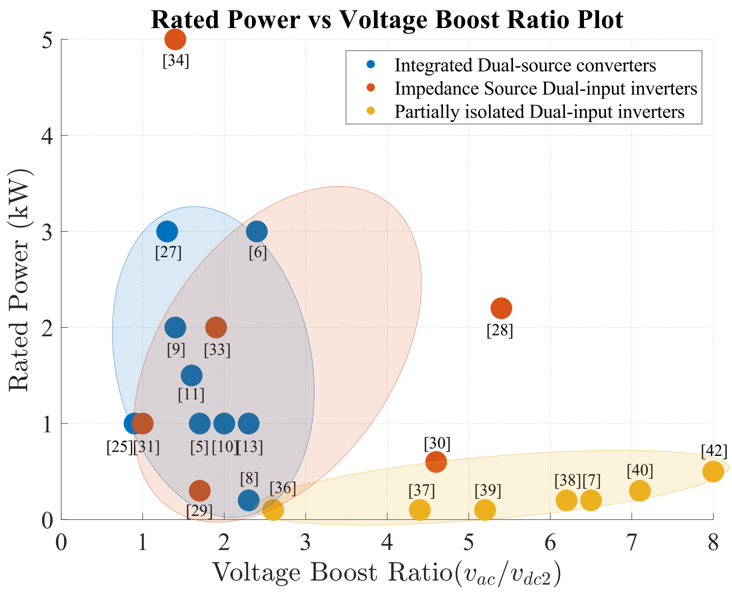


Fig. 6: Rated power against voltage boost capability for dc-dc-ac converters.

the required currents. The second category (Impedance source dual-input) uses the shoot-through state enabled by the impedance network to perform buck-boost functionality at the same time of the dc-ac conversion. Reported controllers for the topologies in this category include single-variable controllers acting on the shoot-through ratio to regulate the dc-dc conversion and on the modulation index to regulate the dc-ac power transfer. The last category (Partially isolated dual-input) uses a high-frequency link, working with the phase-shift angles to perform the dc-dc-ac power conversion. Publications for these topologies show that double- or triple-phase shift modulations can be used to regulate the power flow, using multi-variable controllers to obtain the duty cycles and phase-shifts.

The power rating of the different categories is a main parameter to take into account for a comparative study, as it defines the possible applications for the different categories. Additionally, the voltage boost capability is also a key feature to analyse, as single-stage dc-dc-ac converters have been proposed to replace two-stage solutions to connect low-voltage dc sources to the ac grid. Figure 6 shows a plot that relates these two variables for topologies in the three defined categories. The integrated dual-source converters present a maximum boost ratio of 2.4, as for greater values the power range gets too reduced and losses increase. The impedance source dual-input converters could reach higher voltage gains, but at expenses of increasing the passive components count. The plot shows that the first two categories cover a similar area of higher rated power but limited voltage boost ratio. On the contrary, the third category presents very high voltage ratios but low power rating due to the high-frequency isolation stage. Voltage gains up to 8.0 are reported in literature for this category, with rated powers less than 0.5 kW.

Finally, Table III summarises the features and limitations of the defined categories using one topology as example for each of them.

Conclusion

This article presents a categorisation for the emerging single-stage dc-dc-ac converters, defining three main groups based on the operation principle of the studied topologies. Each group uses different degrees of freedom to perform dc-dc and dc-ac power transfer simultaneously, without requiring additional power converters. The components count differs between the defined categories, as they include either passive or active components to enable the use of the required degrees of freedom. The reported converters have been proposed for low- and medium-power applications and for different voltage boost ratios between the dc ports and the ac one. Moreover, it is shown that each category covers a different range considering the rated power and voltage gain ratio. The first two categories (Integrated dual-source

Table III: Single-stage three-port dc-dc-ac topologies comparison

Reference	Category	Topology	Features	Limitations
[8]	Integrated dual-source	Split-source	Single-stage boost	Unidirectional power flow Low dc-link utilisation
[6]	Integrated dual-source	Buck-boost TPC	Bidirectional power flow Minimum device count	Inductors losses Common-mode voltage
[5]	Integrated dual-source	DP-AMI	Boost capabilities Reduced losses	Reduced power range
[28]	Impedance source dual-input	Z-source	Bidirectional power flow	Reduced dc voltage range
[31]	Impedance source dual-input	Quasi-Z-source	Reduced active devices count Continuous dc currents	Unidirectional power flow Reduced power range
[7]	Part. Isolated dual-source	DAB based	Soft-switching capabilities Galvanic isolation	Low power capability High active devices count

converters and Impedance source dual-input converters) are suitable for applications with higher power requirements and lower voltage boost needs. The remaining category (Partially isolated dual-input converters) is adequate for low-power applications with high-voltage boost requirement.

Hybrid dc-ac power systems have become an enabling technology for the integration of renewable energies and EVs to the electrical grid. Therefore, the optimisation of power conversion systems to interface multiple dc and ac elements has gained relevance in the last years. In this context, this article aims to help in the standardisation of three-port dc-dc-ac converters to facilitate the state-of-art study for new proposals. Three categories are defined and analysed considering the operation principle, rated power and components count. Firstly, Integrated dual-source converters perform the three-port power regulation by using dc-ac converter legs to perform a dc-dc conversion at the same time. These converters offer limited voltage boost capability (ratios up to 2.4) and present rated powers in the order of 1-5 kW. Thus, they are suitable for applications such as hybrid PV-BES or hydrogen fuel-cells with BES systems. Secondly, Impedance source dual-input converters use an passive components network to enable the connection of the two dc ports with an ac grid or load. This category presents voltage gain ratios up to 5.4 between the dc and ac ports and it is also reported for a range of 1-5 kW in rated power. The main applications for these topologies are hybrid energy storage systems, either connected to the grid or driving electric motors in EVs. Lastly, Partially isolated dual-input converters use a high-frequency isolated link with two dc sources at the primary and an ac port at secondary. The converters in this category have the highest voltage gain ratios (up to 8.0), but the power is limited to less than 0.5 kW. Consequently, these converters are most suitable for PV micro-inverter operation with complementary BES.

A possible direction for the future research in single-stage dc-dc-ac converters include increasing the rated power of the topologies. Commercially available multi-stage solutions for applications such as hybrid EV powertrains, hybrid PV-BES or FC-BES systems are rated for powers from 10 to more than

100 kW. Therefore, studies should be performed to analyse the losses increment and the size of passive components required to extend the power capabilities of the single-stage three-port topologies to match the available multi-stage solutions.

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