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Interlinking converters and their contribution to primary regulation: a review

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ABSTRACT

Classical power systems, which are typically structured in top-down topologies, are gradually evolving towards more decentralized systems comprised by clusters of smart subgrids to cope with the increasing penetration of distributed generation, energy storage systems and controllable loads. These clusters will increase the overall reliability, optimize resource usage and reduce investments in back-up systems. However, tying subgrids via passive devices (tie lines or power transformers) poses certain problems from the point of view of modularity and controllability. They also limit the connection capability of subgrids, as it is expected that systems with different voltage natures (ac and dc) will coexist in the future network. In this context, interlinking converters (IC) have emerged as a universal approach for the interconnection of such subgrids regardless of their characteristics. These power converters not only provide power flow control, but they also improve the power quality of networks through different ancillary services. Therefore, ICs are expected to be the energy routers of the future, smartly connecting and managing the interaction among grids. In the literature several topologies and control techniques have been proposed for this type of converters to transfer power between grids and provide support under contingencies. However, there are no classifications from the point of view of the participation of ICs in the primary regulation of the power system. The aim of this paper is to 1) identify the main characteristics of ICs compared to conventional interconnections based on passive devices, 2) review the most usual IC topologies depending on the nature of the grids they are interconnecting (ac-ac, ac-dc or dc-dc) and 3) analyse and compare the different control approaches for the primary regulation via ICs and propose a general classification based on this analysis regardless of the number of conversion power stages of the IC and the nature and characteristics of tied grids.

1. Introduction

In the last decades, the concern about climate change and the constant increment in power consumption have led to the progressive integration of distributed renewable energy sources (RES) into the power network, such as photovoltaic systems or wind turbines. These systems have actively contributed to reduce greenhouse gas emissions, increase the network power capacity, prevent the saturation of lines, reduce energy prices and improve the overall efficiency. However, the integration of RES into the power network poses certain challenges due to their stochastic and distributed nature and their lack of inherent inertia compared to conventional generation systems [1].

In order to cope with these challenges, classical top-down power systems are evolving towards more modular, controllable and decentralised systems with a higher presence of power converters where distributed resources can be easily integrated without jeopardizing the overall stability (Fig. 1).

Classical electric grids have been usually interconnected via direct connections, using passive elements such as tie lines and/or power transformers in ac systems as shown in the left part of Fig. 1. This method has been used for decades in the power network to provide ancillary services between grids, known as load frequency control [2]. However, direct connections bring several limitations from the point of view of controllability, modularity, stability and voltage compatibility. Power electronics converter-based connections are expected to be the universal approach for the future grid, leading to the interlinking converter (IC) concept [3]. These devices will contribute to the creation of a smarter grid, enabling the regulation of the power flow and actively participating in the market of ancillary services.

Thanks to the evolution of power semiconductors and electronic

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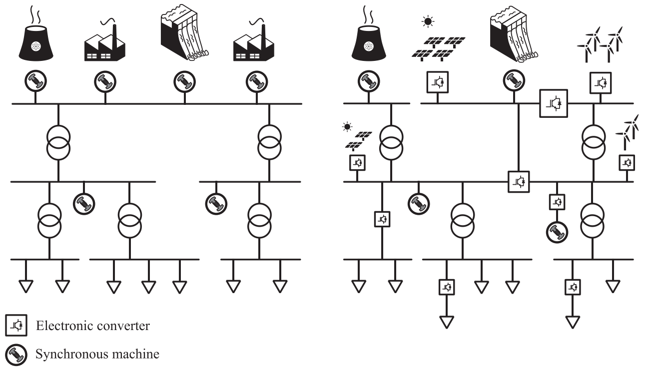


Fig. 1. Top-down structure of classical power systems (left) and future power systems with penetration of electronic converters (right).

components, a clear advantage of interlinking converters is that the concept can be extended to any scope of the power network. ICs can be used for instance in the interconnection of different distribution grids in order to increase the degrees of freedom in the control and management of the exchanged power. Another particular case is the integration of microgrids in the main power system. Microgrids, which have emerged as an interesting solution to cope with the distributed nature of RES, are small scale grids composed of distributed generators (DGs), energy storage systems (ESSs) and loads [4–6]. These microgrids could be benefited from their integration to the main grid via ICs, thanks to the advantages they provide over conventional interconnection systems: grid-connected or standalone operation, power flow control, etc.

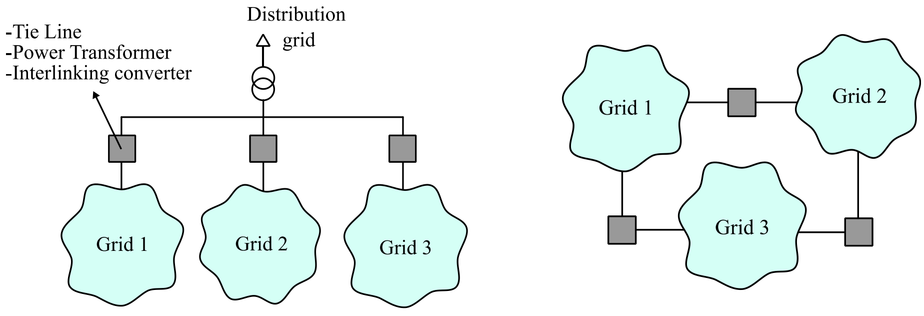
As the number of DGs increases, coordinating them within one single grid becomes more challenging, causing the need to divide it into various independent subgrids or microgrids. In this context, ICs appear as the enabling solution to connect neighbouring systems to form clusters that improve the overall operation [7–11]. In the literature, different approaches for decision making on multiple microgrids (MMG) can be found [12–15].These clusters can be interconnected in a meshed grid or taking advantage of the already existing distribution system as illustrated in Fig. 2 [16]. Regardless of the topology, grid clustering through ICs provides several advantages compared to classical connections:

- The capacity of subgrids is increased without investing in new energy resources or oversizing storage capacity.
- Usage of non-dispatchable resources, such as renewable resources, is maximized.
- The stress and aging of the devices is reduced, decreasing maintenance and increasing the lifespan of the network.
- Energy storage system usage is optimized [7].
- The reliability of the system is increased. Tied systems will support each other, reducing load shedding.

The previous features demonstrate that ICs can bring several advantages compared to conventional interlinking systems such as transformers. These will be more significant with the penetration of dc-based subgrids to the main power system, because ac and dc grids must be interconnected via power electronic converters. Even though most of the distribution grids and microgrids are based on ac to take advantage of the current infrastructure [17,18], dc systems are gaining popularity due to the advantages they offer. For instance, an easy integration of dc-based devices (RESs, ESSs, home appliances, etc.), reduction of conversion stages, increase in efficiency and reliability [19], no reactive power circulation and no need for synchronization can be highlighted [20,21]. These aspects are questioning the unique ac nature of the actual grid [22,23], so in the last years hybrid ac/dc grids have emerged as an intermediate solution that can merge the advantages of ac and dc systems [3,24–26]. In this scenario, ICs will be fundamental for the interconnection of the coexisting ac and dc subgrids.

The main purpose of this paper is to review and identify 1) the distinctive characteristics of ICs compared to conventional interconnections, 2) classify the most common IC topologies based on the nature of the grids they are interconnecting (ac or dc) and 3) review the different primary regulation techniques that have been proposed in the literature for this type of devices. These techniques differ significantly from the ones employed at grid-connected generation or storage devices as the ones reviewed in [3,27–31]. On the one hand, the control philosophy of ICs is different from grid-connected devices because even though they are not capable of contributing to the primary reserve by themselves, they can participate in the primary regulation and provide other ancillary services. On the other hand, unlike in typical grid-connected systems, at ICs the primary and the secondary sides are not fixed by a power source and hence more advanced approaches need to be employed. Another contribution of the paper is that the reviewed techniques are presented in a generalized form, meaning that they will be equally applicable to grids of different nature (ac or dc) and different properties (voltage levels, frequency, etc.).

The rest of the paper is structured as follows: in Section 2, the main features of ICs are mentioned together with the aspects that have to be taken into account when their implementation is considered. Afterwards, power converter topologies for interconnecting grids of different natures—mainly from the point of view of conversion stages—are reviewed and discussed in Section 3. Section 4 covers the different ancillary services that have been proposed for ICs, focusing on the primary regulation techniques that have been proposed in this topic. Some of them have been previously reviewed in [27] and [30], but these techniques are limited to islanded hybrid microgrids and several techniques are not covered. In this section, we propose a general classification for primary regulation techniques with ICs, which is independent of the nature/characteristics of the interconnected grids and the number of power stages of the IC. In the last part of the paper, Section 5 collects some of the most interesting future research trends related to ICs and finally, the main conclusions of the review are summarized in Section 6.



a. Based on distribution network

b. Based on meshed grids

Fig. 2. Grid clustering structures.

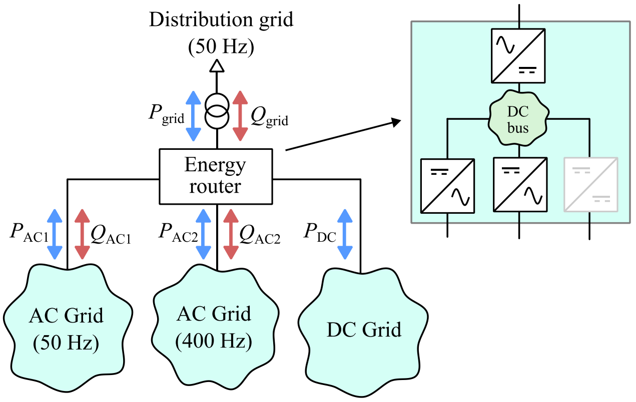


Fig. 3. Energy router concept.

2. Interlinking converter concept

Current power systems are undergoing several changes in their topological structure, shifting from a top-down structure towards a more decentralized and interconnected grid. Even though conventional interconnection devices such as tie lines or transformers have some inherent advantages, their passive nature limits their behaviour to the conditions of the grid. Replacing such passive elements with actively controlled power electronic converters is gaining interest to improve the management of the system. In fact, these power electronic devices, which are also known as interlinking converters, are meant to be key elements in future power systems working as energy routers of the grid [32]. Fig. 3 illustrates a possible future scenario in which an IC is employed to manage the exchange of energy between two decoupled 50 and 400 Hz ac grids, a dc grid and a conventional distribution grid.

2.1. IC features

Some of the most interesting characteristics or functionalities that can be provided through ICs are summarized below:

- **Connectivity regardless of the nature of the grid.** Interconnection of ac and dc grids is only available via interlinking converters, meaning they will play a key role in the future hybrid smart grid scenario [24]. Moreover, ICs enable the asynchronous connection of ac grids with different frequency or dc grids with different voltage levels. In this context, ICs provide extra degrees of freedom to select the optimum voltage and/or frequency of grids.
- **Grid decoupling.** Interlinking converters provide voltage and current decoupling among tied grids. The former prevents voltage sags/swells to propagate from one grid to another, and the latter isolates current harmonics. These harmonics produce extra losses and voltage distortions, and are of high relevance due to the increasing number of power electronic-based devices that incur into potential harmonic distortion [33].
- **Power flow control.** Interlinking converters provide controllability over the exchanged active and reactive power, enabling the direct power flow regulation between grids. Regulation is simplified compared to a direct connection, in which the power flow is controlled indirectly through high-level controllers—which is translated into slow and non-perfect regulation [7]. Moreover, power flow control through ICs could reduce instability problems due to impedance effects [34].
- **Reduced power network complexity.** The interactions between tied systems are primarily handled ICs, making the power network more modular and simpler to control. Unlike directly connected grids, the power network's complexity does not increase as new grids are added. For instance, the connection and synchronization of microgrids is simplified, especially in the case of meshed grids, where several connections could exist at a time. As each tied grid can be independently controlled, ICs might facilitate the *plug-and-play* feature of DGs and loads [35].
- **Contribution to ancillary services.** As other power electronic based solutions, ICs not only can regulate the power flow, but they can also provide ancillary services to the grid. This is a very interesting and promising concept, especially considering that power converters do not operate at the maximum rating all the time. In this sense, ICs can be seen as part of flexible ac transmission (FACT) systems and compete with other existing solutions as discussed in [36]. The ancillary services of ICs have been extensively studied in literature, particularly for solid-state transformer (SST) devices [37,38]. Table 1 gathers the most relevant ancillary services.

2.2. Integration considerations

With the aim of achieving an effective integration of converter-based links among different grids, some aspects of ICs need to be taken into account. The most relevant ones are related to the use of power semiconductors, since they suppose a lower efficiency, lower lifetime, lower reliability and an increment on the cost of devices. Moreover, their overcurrent and overvoltage capability are also limited compared to conventional solutions, leading to extra protection requirements. Even if ICs can contribute to an intelligent fault detection and isolation,

Table 1
Ancillary services provided by ICs.

Ancillary service	Description	Reference
Active power regulation	Even if ICs do not change the net amount of active power in the network, they could participate in its regulation by controlling power transfer among grids. Active power regulation is done through a hierarchical control where primary, secondary and tertiary regulations are distinguished depending on the actuation speed. ICs could participate in all of them.	Primary regulation is covered in Section 4
Reactive power regulation	In ac grids, reactive power must be regulated to keep a stable voltage amplitude and minimize losses. ICs could work as a STATCOM, absorbing or injecting reactive power independently in ac grids.	[39–41]
Harmonic and unbalance compensation	Apart from providing harmonic isolation, ICs could actively contribute to eliminate current harmonics using compensation techniques. Voltage harmonics could also be eliminated using a shunt connection of the IC. Power unbalances can be compensated by controlling each phase independently.	[42–45]
Black start and back-up operation	ICs could play a key role in the black start operation of grids by centralizing the process. In this way, microgrids' devices should require minimum modifications. Moreover, back-up operation could be provided if storage is integrated inside the IC.	[46,47]
Smart protection	ICs can provide intelligent fault detection and current limitation characteristics. Once the fault is isolated, impedance measurement could be used to determine if a fault still exists and reinstate power delivery.	[33,35]
Harmonic and resonance damping	ICs can identify and dampen grids resonances, improving stability. ICs could centralize the stabilization mechanism, simplifying remaining local controllers.	[48]

Table 2
Main features of interlinking converters and direct connections.

	Direct connection	Interlinking converter
Connectivity	AC grids synchronized in phase DC grids synchronized in voltage	Does not depend on voltage nature Asynchronous connection
Power flow control	Indirect	Direct
Voltage/frequency regulation	Error in steady state	No error
Voltage/current decoupling	No	Yes
Ancillary services	No	Yes
Overall complexity of network	Increases with new microgrids	Simple, interaction limited to IC
Cost	Low	High, tending to decrease
Efficiency	High	Moderate, increasing with new semiconductor technologies
Reliability	High	Low
Lifetime	High (> 30 years)	Low (< 10 years)
Design	Simple	Complex
Integration in actual grid	Simple	Compatibility problems

their low short-circuit current capability limits its compatibility with the actual power network [49].

However, the constant reduction of power semiconductor prices and the improvement of this technology will mitigate the problems related to the efficiency, complexity and the cost [50]. In any case, it is expected that direct connections and ICs will coexist in the future power network, being the controllability and contribution to the quality of the grids a key factor [16]. The characteristics of interlinking converters and direct connection are summarized in Table 2.

3. Topological overview of interlinking converters

In the literature, several power converter topologies have been proposed to interconnect different parts of the grid or to form clusters. Different criteria could be followed to classify these topologies, such as the nature of the voltage or the number of conversion power stages. The latter has been used in [30] to review ICs in hybrid islanded microgrids. It has been also used in [51] and [52] to classify solid state transformer topologies.

As one of the goals of this review is to cover different types of connections, for a more general classification the voltage nature of the interconnected grids is selected as the classification criterion. According to this criterion different types of dc-dc, ac-ac and ac-dc interlinking converters can be found in Table 3. Inside each group, two scenarios are distinguished: the first one considers a subgrid connection with the main grid (e.g. a microgrid), whereas the second one refers to grids being connected together. The most common topologies of each group will be discussed in the following subsections.

3.1. DC-DC interlinking converters

As it has been mentioned before, dc grids have gained popularity in recent years due to the advantages they offer compared to ac systems [20]. For instance, the lack of reactive power in dc systems limits the requirements to active power control and these converters have the advantage of being a simpler and more economical solution. In addition, they provide greater reliability, as the number of power semiconductors is reduced compared to other topologies. However, the interconnection of grids via dc-dc converters needs to be studied more in detail, as it is the least studied case according to Table 3.

Table 3
Classification of ICs regarding the nature of tied grids.

Nature of grids	Grid type	Converter type	References
DC-DC	Subgrid – grid	Dual active bridge	[53]
	Grids	Buck/boost	[54,55]
		Dual active bridge	[56–60]
		Flyback	[61]
AC-AC	Subgrid - grid	Back-to-Back	[32,62–65]
		SST	[37,46,66–69]
	Grids	Back-to-Back	[32,39,70–75]
AC-DC	Subgrid – grid	2L-VSI	[42,76–79]
	Grids	2L-VSI	[43,80–100]
		Back-to-Back	[44,101]
		Buck/boost + VSI	[85,102,103]

Buck/boost based solutions have been suggested to connect islanded microgrids with similar voltage levels [54,55]. However, isolated bidirectional dc-dc (IBDC) converters are selected when galvanic isolation or a big voltage step is required (for instance, 48 V − 380 V connections). The most usual isolated converter is the dual active bridge (DAB) [53,56,57,59,60], but flyback topology has been also suggested (e.g. in [61]). All of them can be considered as one-stage interlinking converters.

One of the interesting features of IBDC converters is their multiport capability. A single power converter can be modified to provide several isolated dc ports, each one with its own voltage level. Under multiport operation, several dc microgrids can be connected and exchange power with minimum semiconductor-related power losses. Multiport operation of these ICs has been suggested in [57,58,61]. Another key feature of the dual active bridge topology is that zero voltage switching (ZVS) operation is easily achievable, which increases the power exchange efficiency by eliminating switching losses even in multiport operation [57].

In general, dc-dc ICs could be used in dc-based systems such as aircrafts or ships [58]. In this sense, dc grid connection does not only improve system reliability, but also provides a more efficient route for power exchange between grids, eliminating the saturation of grid lines. This concept is shown in Fig. 4. The red line represents the original power flow, which should go through two ac-dc stages, two transformers and a power line. The blue line shows the alternative power route that provides the dc-based power converter. The connection of dc subgrids to a dc grid (tied or isolated from main grid) has also been suggested with the aim of improving efficiency and reliability [53].

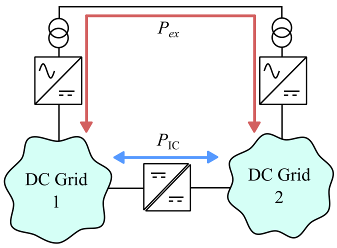


Fig. 4. Alternative power flow provided by DC-DC IC in tied microgrids.

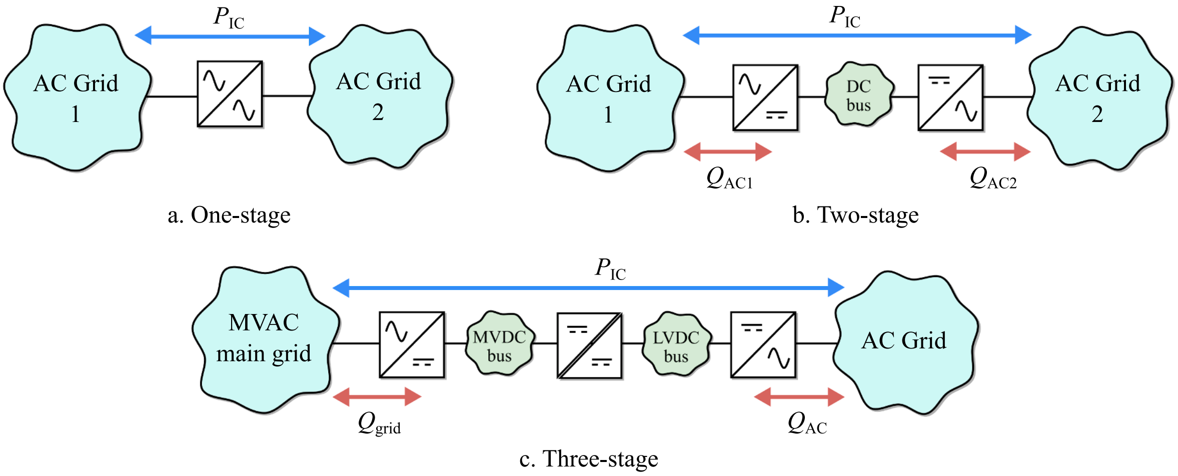


Fig. 5. AC-AC interlinking converter topologies.

3.2. AC-AC interlinking converters

The connection of ac grids has been mostly done through power transformers, as they provide a simple and efficient way to link lines of different voltage levels with galvanic isolation [17]. However, as it has been seen before, ICs bring several advantages related to active and reactive power flow control compared to these conventional connections. ICs that interconnect AC grids can be distinguished into one-, two- or three-stage power converters.

Regarding one stage ICs, direct matrix converters can be used as shown in Fig. 5a. Their main advantage is the direct conversion of ac voltage without an intermediate dc buffer [104]. However, this characteristic leads to a significant voltage coupling and limits the reactive power regulation in both sides. It has also some drawbacks, such as a high number of power semiconductors, limited output voltage amplitude, control complexity and high input/output filter size. Even if advanced matrix converters have been suggested in literature, they have not been used for interconnecting ac grids and therefore they are not covered in detail in this review.

3.2.1. Two stage ac-ac interlinking converters

The Back-to-Back topology (B2B), which is shown in Fig. 5b, has been extensively used in high voltage dc transmission [105] and is the most common IC topology for connecting ac grids [32,39,70–75]. Apart from providing full active power flow management, the intermediate dc bus decouples both ac grids, leading to independent reactive power regulation and ancillary services in both sides of the IC. When a voltage step up/down or isolation is required, a power transformer must be included in one of the sides at the expense of increased cost and reduced efficiency. An example is the case of microgrids connected to the distribution grid [63].

The intermediate dc bus can be used to create a dc microgrid for the integration of generation, storage systems and/or loads. In this context, B2B topologies can be analysed as two independent interlinking converters that connect an ac and dc grid (explained in Section 3.3), instead of a two-stage ac-ac converter.

By employing this approach, a hybrid ac/dc microgrid connected to the distribution grid is proposed in [65], whereas [106] integrates an electric vehicle charger using the dc bus. In [63], the B2B converter that connects the microgrid with the main grid includes a battery. This battery can be used to absorb power perturbations and improve power quality in both sides of the IC or achieve back-up operation under main grid faults. The B2B has also been suggested to work as an energy router interconnecting several asynchronous ac grids using its dc bus, which is also known as a multi-terminal dc grid [32,64,71,107]. The study in [64] extends the work of [63] using the battery in the dc bus as a common storage for all the connected ac microgrids, which could reduce storage investment.

B2B topology has also attracted interest in radial distribution grid connections [108]. The power converter, located at the rear end of the line, can work as a FACT that regulates voltage fluctuations produced by the stochastic character of RESs [109]. It also provides active power control between distribution lines, maximizing the usage of renewable resources. All in all, including ICs reduces power losses, ensures back-up operation under main grid faults and prevents the oversizing of grids. A common storage system has been also proposed in [110] for distribution lines.

The main drawback of this topology is its efficiency, as all the power must flow through two power stages (ac-dc and dc-ac). To solve this problem, direct connections and ICs could be used in combination as proposed by [111]. The concept is shown in Fig. 6. The power transformer allows an efficient power exchange with the main grid, whereas the B2B connection could be used to control power flow, provide ancillary services and achieve redundancy under grid faults. A similar approach is shown in [74], in which single-phase B2B converters are used to interconnect phases in a 3-phase system. In this case, each phase could be considered an independent subgrid that directly exchanges power with the main grid, being the function of the B2B to achieve equal power sharing, fully utilization of DG and emergency back-up with reduced power rating.

3.2.2. Three stage ac-ac interlinking converters

Solid state transformers can be categorized into this group. SSTs—also known as smart transformers or power electronic transformers—are power electronic based solutions that replace standard low-frequency transformers while providing power flow control and

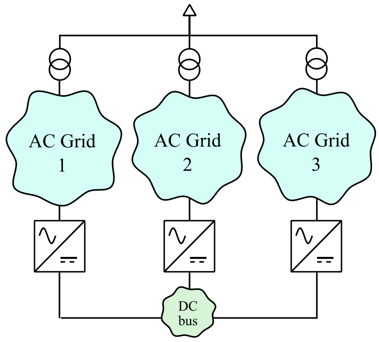


Fig. 6. AC microgrids connected to the main grid and through an IC-based dc bus, also known as multi-terminal dc grids.

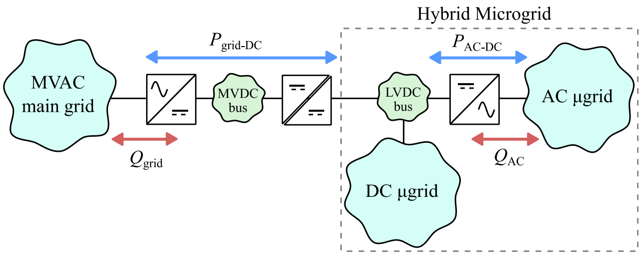


Fig. 7. Hybrid ac/dc microgrid created through an SST topology.

ancillary services [52]. From the point of view of subgrid interconnection, the 3-stage SST topology is the most used one, even if other topologies can be also employed [51]. A simplified diagram is shown in Fig. 5c. The main difference with the B2B topology is the intermediate IBDC stage, usually a dual active bridge converter. This third stage could provide galvanic isolation and a high voltage step up/down capability, using a medium frequency transformer which increases power density compared to conventional power transformers.

Due to the high number of power stages, SSTs have more degrees of freedom than previous topologies. Apart from interconnecting ac grids regardless of their voltage levels and achieve galvanic isolation, they also provide isolated medium voltage (MVDC) and low voltage (LVDC) dc buses. As in the previous B2B topology, they could be used to integrate storage systems or to form other dc grids. Most of the literature has focused on the LVDC bus. For instance, in [112] a supercapacitor based storage system has been included to increase the ride-though capability. Hybrid ac/dc microgrid integration using its low voltage ac and dc buses are common in the literature [66,68,69]. A simplified representation of this configuration can be seen in Fig. 7.

SSTs have been extensively studied in the recent years. For example, the different topologies from the point of view of the power flow and the type of connection have been covered in [51,52]. Moreover, several projects have developed experimental SST devices, such as UNIFLEX, EPRI, GE or FREEDM, which are summed up in [113]. As they handle high input voltages and high output currents, the topology and design of these ICs is complex. Moreover, their efficiency, cost and reliability problems are increased due to the high number of power stages. Even if SSTs could be considered ac-ac power converters, they are only expected to be viable when the use of the dc link is increased, e.g. at hybrid or dc grid integration [114]. In the remaining cases, and as suggested by [49], cheaper, simpler and more efficient topologies could be used while keeping grid controllability and ancillary services.

3.3. AC-DC interlinking converters

AC-DC converters have been the most studied ICs in the recent years according to Table 3. The connection between ac and dc grids has been extensively studied through the hybrid ac/dc grid concept, focusing on the power management through the interlinking converter [79–90,92,95,97–100] In addition, these topologies are required to connect the emerging dc-based systems to the main ac grid [75–78].

The literature has primarily focused on low voltage systems, and 2-level voltage source inverters (2L-VSI) have been used for example to interconnect hybrid microgrids. This topology is a simple, one-stage power converter that achieves full active power flow control between grids and reactive power regulation in the ac side. For higher voltage levels, more complex topologies such as modular multilevel converters have been suggested [111].

When ac and dc grid voltages are not suitable for a VSI, a power transformer might be added in the ac side. Another approach is to use a two-stage IC composed of dc-dc and dc-ac stages [85]. The latter provides an intermediate dc bus that increases decoupling and that could integrate energy storage devices as previously seen for ac-ac converters. In this context, [102] and [103] have proposed to replace the dc bus by batteries. In fact, the IC could work as a centralized energy storage system for both subgrids, reducing storage investment and improving the overall efficiency. A two stage ac-dc power converter could also be used to connect the MVAC distribution grid with dc subgrids using IBDCs and dc-ac power stages [49]. This topology could bring some advantages: on the one hand, the power density is increased by eliminating the conventional power transformer; on the other hand, a MVDC bus is available, which might be interesting for certain applications such as RES or electric vehicle integration.

An alternative topology is proposed in [44] and [101], where the dc bus of a unified power quality conditioner is used to integrate a dc microgrid within an ac microgrid. This power converter requires two ac-dc stages, even if power exchange is mainly done through one of them. The device has shown its capability to improve the voltage and current quality while exchanging power between grids.

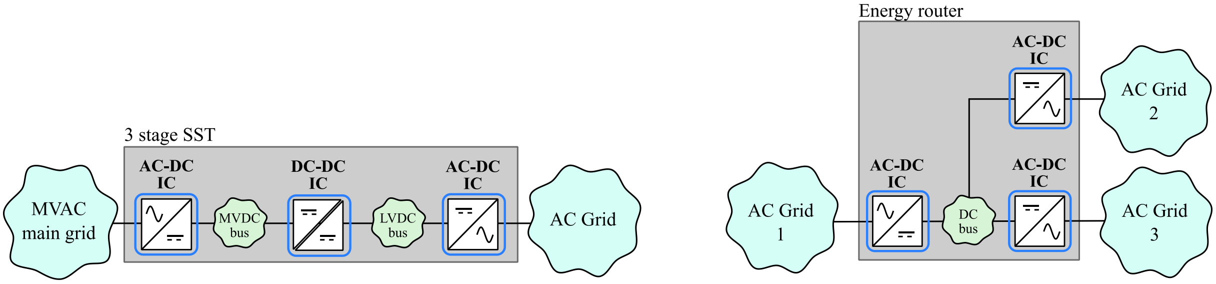
4. Contribution of interlinking converters to primary regulation

As ICs allow active and reactive power flow control, they play a crucial role in the voltage and/or frequency regulation of interconnected grids. The classical regulation of the current power network is achieved through a hierarchical control, where three control levels are predominant: primary, secondary and tertiary [2]. This review is focused in the contribution of ICs to the primary regulation, in which the balancing between the generated and consumed power is handled in steady-state. The basic concept behind the primary regulation resides in providing some sort of regulation under voltage or frequency deviations. Classically, the primary regulation of a DG or ESS is done exchanging power with the grid proportionally to the deviation of the voltage or frequency at the point of connection. This type of primary control is a proportional regulation and is known as *droop control*. Many other approaches have been proposed in recent years e.g. related to devices connected to microgrids [3,27–31], but no review nor classification can be found related to the contribution of ICs to the primary regulation. The latter differ primarily in that the active power control philosophy is not the same, as ICs do not have any energy source that establishes their primary side voltage. This means that they are not a part of the primary reserve of the system and are only capable of transferring power between different parts of the grid.

The aim of this section is to propose a general classification of active power regulation techniques extending the ones existing for classical grid-connected DG systems or ESSs [115]. As the reactive power regulation of ICs does not differ from classical systems (in which each ac side is controlled independently), it is not covered in this review [39]. Secondary and tertiary regulation strategies will be very similar to the ones employed in classical power systems and therefore they are also out of the scope of the review [76,88,100,116].

In order to achieve a generalized classification of the primary regulation of ICs, the following considerations are taken into account:

- A *n*-stage IC can be considered as *n* independent ICs that connect $n + 1$ grids. It means that internal dc bus(es) of multi-stage ICs can be seen as dc grids that require primary regulation. By applying this concept, primary regulation analyses can be simplified to one-stage ICs regardless of the number of stages or number of microgrids that they connect. This concept is shown in Fig. 8a for a 3-stage SST, where two ac-dc and one dc-dc connection can be distinguished. Similarly, Fig. 8b shows an energy router concept based on the B2B topology, which can be analysed as several ac-dc converters [32].
- If variables are normalized using a per unit system (p.u.), the primary regulation analysis can be carried out regardless of the nature (ac or dc) of the interconnected grids [89]. Even if active power regulation is related to frequency/angle in ac inductive grids and to voltage in dc grids, previous studies have demonstrated their equivalence [117–119] and a per unit notation can be used to compare the reserves of both grids. A usual normalization is shown



a. SST analysis

b. Energy router analysis

Fig. 8. Simplification of multi-stage ICs into single stage ICs for primary regulation analysis.

in (1) and (2), where f_{ac} and V_{dc} are measured values, f_{ac}^{max} and V_{dc}^{max} are maximum allowed values and f_{ac}^{min} and V_{dc}^{min} are the minimum ones.

$$x = \frac{2f_{ac} - (f_{ac}^{max} + f_{ac}^{min})}{f_{ac}^{max} + f_{ac}^{min}} \tag{1}$$

$$x = \frac{2V_{dc} - (V_{dc}^{max} + V_{dc}^{min})}{V_{dc}^{max} + V_{dc}^{min}} \tag{2}$$

Taking into account the previous considerations and the hybrid ac/dc microgrid analysis in [25], the proposed classification for primary regulation techniques is shown in Fig. 9. As for DG systems, two main primary control types can be defined for ICs, namely *grid-supporting* and *grid-forming* controllers. Each of these can be then subdivided into single grid and dual grid operation, depending on whether the IC contributes in the regulation of one of its sides or both of them.

In this context, dual grid operation is one of the most interesting alternatives for the primary control of ICs, and Table 4 gathers the most relevant approaches that can be found in literature.

Table 4
Dual grid primary control techniques for ICs.

Dual grid technique	References
Dual droop	[39,56,70–72,81,91,103]
e-droop	[85,89,95,116]
Proportional power sharing	[56,59,75,84,86,94,96,99,100,102]
Other strategies	[27,44,60,82,120]
Mixed droop	[77,83,92–94,97]

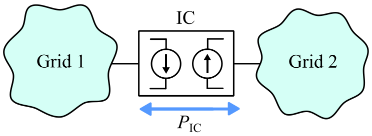


Fig. 10. Grid-supporting operation of IC. An equivalent current source is seen by each grid.

4.1. *Grid-supporting interlinking converters*

In this approach, ICs participate in the active power regulation working as current or power sources as shown in Fig. 10. The IC does not establish the frequencies and/or voltages of the grids, and therefore, it should operate along grid-forming devices. Inside grid-supporting operation, two main operation types can be defined: single grid-supporting and dual grid-supporting modes.

Constant power source mode, in which power setpoints are received from a high level control, could also be integrated inside this group [60,62,65]. However, it does not directly support primary regulation, and hence, it is out of the scope of the review. This operation could prevent large power variations of different parts of the grid from being transferred to the main grid and therefore improve its stability. It could also provide a smooth operation in contractual arrangement, where the power exchange is pre-set.

4.1.1. *Single grid-supporting interlinking converters*

In single grid-supporting operation, the IC contributes to the primary regulation of one of the connected grids, working as a DG system that extracts/absorbs power from a grid instead of an energy source. It is usual in scenarios where the active power reserve of one grid is higher than the other, such as microgrids connected to the main power network. In such cases, the IC supports the grid with the lowest primary reserve, meaning that it is equivalent to a load from the point of view of the system with highest reserve and a generator from the perspective of the system with the lowest reserve.

Under this operation, ICs and DG systems controls are equivalent, and both communicated and non-communicated methods are available. Inside communicated techniques, authors have suggested for instance master-slave controls [27,98] or centralized controls [54,55,90,91]. These allow an improved power quality and regulation compared to

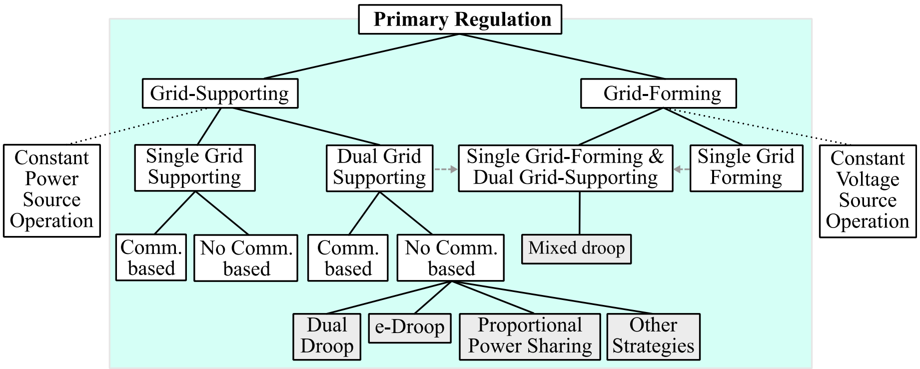


Fig. 9. Classification of primary regulation techniques of ICs.

non-communicated methods. However, they are complex, require high investments and their reliability depends on effective high-speed communication systems. Moreover, they cannot be generalized, as they heavily depend on the system characteristics. The literature about ICs has mainly focused on non-communicated droop techniques, as they are simple, reliable and enable the *plug & play* operation of devices. The equation of the grid-supporting droop technique is shown in its normalized form in (3).

$$P^{*} = P_0 + \frac{1}{m}(x_0 - x) \tag{3}$$

The power setpoint P^{*} of ICs depends on the deviation of the measured voltage/frequency x at the connection point with respect to its nominal value x_0. P_0 is the power command and m is the droop coefficient. Examples of this droop technique can be found for instance for dc microgrids connected to the main grid [76,81]. It has been also proposed in [58] for a multiport IBDC that connects three dc microgrids.

4.1.2. Dual grid-supporting interlinking converters

In dual grid-supporting operation, ICs contribute to the primary regulation by taking into account the active power reserves of the two grids they are interconnecting. In this mode, which is particular of ICs, the power converter plays a key role in achieving the active power balance and supporting both grids under contingencies such as overloading and underloading conditions [95,121]. This approach has been mainly suggested for connecting grids with similar active power reserves, such as islanded microgrids, where this operation could achieve a more stable primary regulation [75].

As in single grid-supporting operation, both communicated and non-communicated techniques can be used. Previously mentioned communication methods can be easily adapted to operate on dual grid-supporting mode, at the cost of increasing the communication network to both grids [54,91]. In the case of non-communicated methods, authors have developed several modified droop techniques, in which the active power regulation of both grids is achieved using measurements of their voltage and/or frequency. The most popular techniques include the dual droop, e-droop or equal power sharing.

Dual droop

In this method, the droop Eq. (3) is applied on each side of the IC. The total active power setpoint of the converter will be the difference of the power obtained by each droop equation as illustrated in Fig. 11. In this way, the status of both grids is considered in the primary regulation and power is transferred to the grid with the biggest demand, balancing the power deviations in both grids. Droop curves should be chosen in a way that the total power rating of the IC is not exceeded.

The main drawback of this method is that the overall droop curves of both grids must be known to define the droop coefficients of this technique. They are usually obtained based on the knowledge and fixed assumption of the droop characteristics of the devices connected to the grid. However, malfunction could occur as setpoints and droop values change depending on several factors, such as disconnections due to maintenance or addition of new systems.

Different operation modes can be achieved depending on defined droop curves. The IC could work continuously under voltage perturbations as suggested in [56]. However, it is also possible to define thresholds which improve system efficiency and prevent the operation of ICs for instance under low power demands [81]. More advanced techniques suggest the segmentation of droop curves, in which power transfer can be limited to overload and underload conditions of the connected grids [91]. The latter is suggested e.g. in ac grid interconnection where the IC is designed to focus in reactive power compensation and minimize active power transfer to improve overall efficiency and simplify the control of DG systems [39,70].

In [72], the dual droop concept has been applied to each ac-dc converter of a B2B topology and it is suggested to integrate ac and dc microgrids. AC multi-microgrid connection based on B2B topology has been also proposed in [71]. In this case the IC is controlled as a whole, and the intermediate dc bus voltage regulation is included inside the dual droop algorithm. Finally, [103] has applied a dual droop technique on a two stage ac-dc IC with batteries in the intermediate bus. The storage system, which includes its own droop control, allows extra power management capability and primary regulation decoupling. For instance, this topology allows the IC to provide regulation even during underloading (battery charging) or overloading conditions (battery discharging) of both grids.

As mentioned in [70], dual droop operation could be easily adapted to single grid-supporting mode by disabling one of the droop curves. In this sense, single grid-supporting mode could be seen as a particular case of dual droop approach, in which one of the droop curves is not employed.

e-Droop

In the e-droop technique, the normalized deviation between connected grids is used for the droop equation. The deviation e is shown in (4), and it is obtained from the measured and normalized voltages and/or frequencies of both grids (x_1 and x_2). A value $e < 0$ indicates that grid two is dominating the neighbouring grid one and active power should be transferred to the latter one. When $e > 0$, grid one dominates grid two. The simplified schematic is shown in Fig. 12.

$$e = \frac{x_1 - x_2}{2} \tag{4}$$

This method only considers the normalized deviation and does not require information about the overall characteristics of the grid, making it simpler than the dual droop technique. However, as it is based on a single droop curve, it provides less flexibility from the point of view of a power flow optimization. Similar to the dual droop, ICs controlled with the e-droop technique can operate continuously or thresholds can be

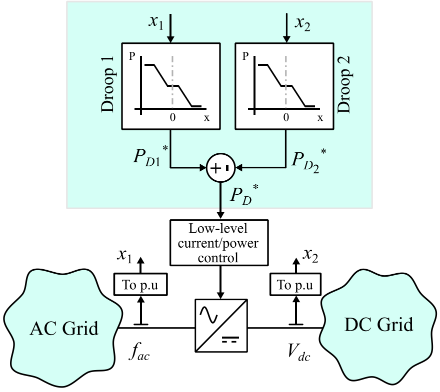


Fig. 11. Dual droop control of an ac-dc IC.

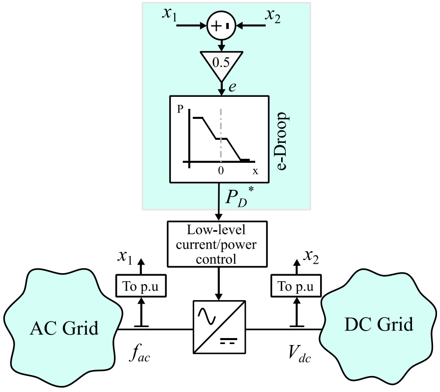


Fig. 12. e-droop control of an ac-dc IC.

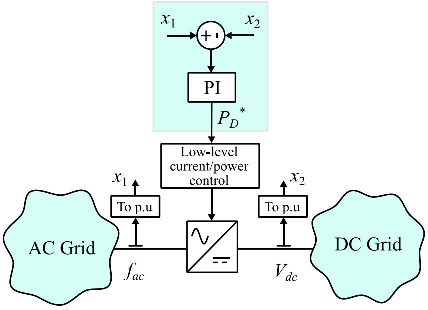


Fig. 13. Proportional power sharing control of an ac-dc IC.

defined to prevent power exchange e.g. when grid deviations are below a certain limit, as proposed in [89].

This concept has been mainly applied to hybrid grids [85,89,95], but it could be extended to other current natures. For instance, [116] suggests the *e*-droop in a community microgrid, where ICs are used to connect ac and dc microgrids to a common ac bus. The ICs in this case contribute in the primary regulation of the microgrid and the ac bus. Moreover, upper-level secondary and tertiary controls are included, proving *e*-droop compatibility with hierarchical control.

Proportional power sharing

It allows two grids to share active power proportionally to their nominal capacity. This results in equal loading factors of grids and proportional power share among all DGs in the system [102]. In this sense, the IC could be seen as a universal transformer.

The simplified control diagram is shown in Fig. 13. The normalized voltages/frequencies of both grids are equalized, eliminating the deviations through a PI. Proportional power sharing is a simple technique for handling ICs, but it has some drawbacks: on the one hand, it does not allow parallel operation of ICs due the PI-based regulation; on the other hand, continuous operation of ICs produces unnecessary losses at low loading conditions [89].

Proportional power sharing is one of the most employed techniques and it has been applied in ac-ac [75], dc-dc [56] and ac-dc [96] connections. In [99], both *e*-droop and proportional power sharing concepts have been used in parallel. By adjusting the bandwidth of the PI, the *e*-droop can be used as a primary regulation technique or participate in a higher level of the hierarchical control. In [59], the active power reserves of grid-forming devices are only considered. In this way, the IC equalizes the loading factors of grid-forming devices and achieves a more reliable operation from the primary regulation point of view. A two-stage ac-dc IC with intermediate storage is proposed in [102]. Apart from achieving proportional power sharing, storage systems provide a higher flexibility in the primary regulation of the whole system. Ref. [100] has included modified secondary and tertiary regulations on a hybrid IC working with this technique.

In the case of dc grids, dc voltage is a local variable that depends on line impedances and a proper power sharing might not be achieved due to voltage drops. The same problem occurs in the reactive power regulation of ac grids. In this context, modified normalized variables have been used to ensure equal loading factors. For example, the authors in [96] have introduced normalized active and reactive power control indices. In [84], common ac and dc voltages are defined. Both papers have shown better results than conventional proportional power sharing technique, but their main drawback is that line impedances must be measured or identified.

Proportional power sharing could also be achieved with alternative algorithms. In [86], a dual droop control with adaptative coefficients is used in a data driven model-free adaptative voltage controller. In [94], a mixed droop technique with proportional power sharing capability is proposed (covered in Section 4.2.2). In both cases, grid-forming operation is also achieved.

Other strategies

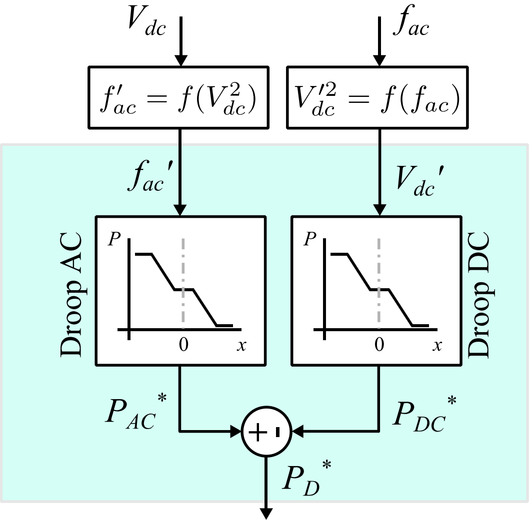


Fig. 14. Hybrid ac-dc droop concept.

Various authors in the literature have also suggested other dual grid-supporting techniques that have not been classified in the previous groups.

As an example, the IC could provide frequency/voltage restoration capability as suggested in [60] and [120]. When one of the measured variables goes below a predetermined boundary (overload or underload condition), the IC will transfer a constant power that restores the normal operation of the grid, preventing load shedding and activation or deactivation of extra DGs. This operation could be considered as a secondary level control, as it eliminates voltage and frequency deviations.

Finally, certain authors have proposed a hybrid ac-dc droop technique, which can be seen as a modified dual droop applied in ac-dc grids [27,44,82]. Instead of using normalized variables, the relation between ac frequency and dc voltage is obtained using the dc bus dynamics, in the form $f_{ac} = f(V_{dc}^2)$. This relation is used to obtain the dc voltage deviation from the ac frequency measurements and vice versa. Obtained deviations are afterwards applied in a dual droop structure. The concept is shown in Fig. 14.

4.2. Grid-forming interlinking converters

In this case, the IC participates in active power regulation working as voltage source for one of the interconnected grids, as shown in Fig. 15. The IC could for instance regulate the voltage of one of the grids, reducing the need for additional energy storage systems or grid-forming devices. Moreover, the stability of the grid might be improved compared to grid-supporting operation, especially during load transients where oscillations can be large and beyond allowable limits [83]. One of the disadvantages of this approach is that it does not include direct current control, which is especially important during faults and disturbances, and usually extra control loops have to be added.

Similar to grid-supporting ICs, the grid-forming operation could be divided into two different modes of operation: single grid-forming and single grid-forming + dual grid-supporting operation. The IC could also set a fixed voltage regardless of the grid conditions, working in constant

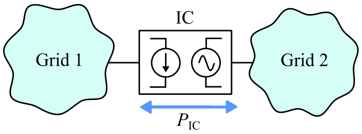


Fig. 15. Grid-forming operation of IC. An equivalent voltage source is seen by one of the grids.

voltage source mode. However, this mode is not considered in the review as it does not directly participate in power regulation [42,63,78].

4.2.1. Single grid-forming interlinking converters

As in single grid-supporting operation, this mode will only contribute to the primary regulation of one of the grids. The operation is equivalent to a DG system, and the well-known droop Eq. (5) is used. The main difference of this approach compared to the single grid-supporting technique is that instead of setting an active power reference based on the frequency or voltage we measure, we invert the droop controller previously shown in (3) to set a certain voltage or frequency (x^*) based on the measured active power and the established reference. This technique can be hence considered as the inverse of the single grid-supporting strategy.

$$x^* = x_0 - m(P_0 - P) \tag{5}$$

As we have already mentioned, this operation is considered when grids with different active power reserves are connected, for instance, to regulate the low-voltage ac and dc sides of SST-based hybrid microgrids [66,69] or in islanded hybrid microgrids where power reserves are mainly storage devices in the dc side [87,88].

4.2.2. Single grid-forming + dual grid-supporting interlinking converters

This approach can be considered as a combination of single grid-forming and dual grid-supporting operations, and hence, it is limited to ICs. The power converter will contribute to the primary regulation of both grids but working as a voltage source for one of the grids.

Under this sub operation, mixed droop techniques are included, where the droop equations of both grids are combined to achieve a new equation. With this approach, the voltage/frequency setpoint of one grid is obtained from the measurement of the other grid and the power transferred by the IC. Its typical structure using normalized values is shown in (6), where k_1, k_2 and k_3 are constants. The mixed droop equation can be seen as a conventional droop in which the voltage/frequency command (x_0) is obtained from the measurement of the other grid. The simplified scheme is shown in Fig. 16.

$$x_1^* = k_1 + k_2 x_2 + k_3 P_{IC} \tag{6}$$

Mixed droop equations have been mostly used in hybrid microgrids to regulate the ac-side frequency, as this technique does not require frequency measurements [77,83,93,94,97]. This avoids the use of a synchronization unit (e.g. a phase-locked loop or PLL), improving the system stability.

The authors in [94] propose a simple droop equation which does not require the third component of (6), achieving a proportional power sharing of the grid. The ac side active power and frequency fluctuations are improved by applying the synchronverter concept. In [93] and [97], proportional power sharing or droop behaviour can be selected changing the coefficient values or operation mode (grid-connected/islanded). A more sophisticated mixed droop is proposed in [83], which includes inherited overloading protection for the IC. Even if ac side is usually selected, the same concept could be applied for the dc bus side voltage regulation, as suggested in [92].

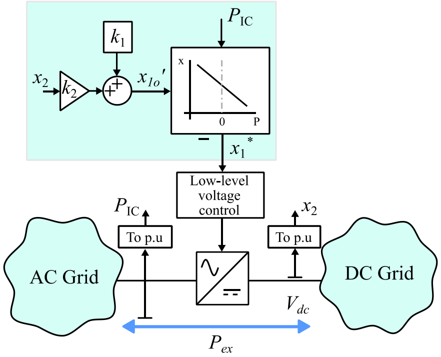


Fig. 16. Mixed droop equation of an ac-dc IC.

Finally, as proposed in [77], it is possible to mix the droops of both sides with the synchronous machine mechanical equation, also known as *swing equation*. The authors show a dc microgrid tied to the main grid through an IC that provides not only dual grid-supporting operation, but which also behaves as a synchronous machine from the main grid point of view. The IC prevents perturbations from being directly transferred to the main grid, enhancing stability.

5. Future trends in interlinking converters

This review has analysed the advantages and disadvantages of current ICs, their topologies and their primary regulation techniques. There are studies in the literature that have also focused on the contribution of these converters to ancillary services. However, certain aspects should be studied in detail to achieve the practical implementation of ICs. Some potential research gaps identified during the review process include:

- **Optimal power converter sizing, design and location:** efficiency, reliability and cost problems should be improved through an adequate design. Due to the SST complexity, its design has been a field of study in the recent years and great advantages have been achieved with the appearance of wide-bandgap semiconductors. However, interlinking converters optimal sizing and location has not been considered and could also lead to a higher efficiency and reduced cost of the system.
- **Inertia emulation:** the equivalent rotational inertia reduction is a well-known problem related to the continuous integration of power electronic-interfaced devices (DG, ESSs and loads), which is translated into stability and grid regulation issues. ICs will not only decouple the voltages and currents of the interconnected grids, but also their inertial behaviour, aggravating the actual problem. Several primary regulation techniques have been already proposed and are reviewed in this paper, but the emulation of inertia through ICs has been hardly ever considered [77,94,122–124]. Its impact in the grid and its benefits should be thoroughly studied.
- **Stability analysis:** most of the papers that have studied the primary regulation of ICs include small signal stability analysis. However, there is a need to develop large signal models which predict the performance of the system under wide-range variations. Moreover, both steady-state and dynamical stability should be considered.
- **Operation under non-ideal conditions:** ICs primary regulation techniques have been analysed under ideal conditions, considering balanced systems and ideal loads. However, they should be evaluated in more realistic conditions e.g. considering system faults, unbalanced ac systems or harmonics in the grid caused by nonlinear loads or the interactions with other power electronic converters. In that sense, the primary regulation should be tested with other ancillary services such as harmonic compensation, fault limitation or active damping techniques.
- **Parallel operation of ICs:** using several power converters can increase the reliability under power device faults and increase efficiency by dynamically selecting the number of active converters. Also, different control techniques and ancillary services can be provided by each IC. Unlike communicated techniques, droops have shown problems achieving power sharing due to the local nature of the measured voltage and the effect of line impedances. In the parallel operation of ICs, this can be translated into circulating currents that might lead to unwanted losses and decreased efficiency. Different approaches such as virtual-impedances must be analysed to tackle these problems [92].
- **Protection compatibility:** ICs have a low overcurrent and overvoltage capability compared to tie lines and power transformers. In

this sense, new protections and fault management architectures should be proposed to ensure the security of power networks under faults or perturbations [62].

- **Multigrid connection:** most of the research has focused on interconnecting two grids (microgrid-grid or microgrid-microgrid). However, ICs are meant to be the energy routers of future grids, connecting several grids at the same time. In this sense, intermediate buses of multi-stage power converters and multiport topologies should be used to integrate grids or storage systems which could be shared among grids. Therefore, multigrid connection performance and challenges should be identified more in detail.

6. Conclusions

Research about interlinking converters has increased in recent years thanks to different factors: a growing interest in SST technology to replace conventional transformers, the increasing penetration of power electronics for the integration of distributed generation and energy storage systems via microgrids (either ac, dc or hybrid ac/dc), etc. In the near future, these power converters will be the energy routers of the smart grid, connecting several grids regardless of their voltage nature and managing their interactions in a smart manner instead of behaving as passive elements.

This review has analysed the main characteristics and functionalities of interlinking converters and the aspects that need to be taken into account in their integration compared to the direct connection of grids. Their ability to simplify the structure of the power network by making it more modular and reconfigurable, to increase its controllability and provide ancillary services appear as some of the most interesting features that could be provided by ICs. Thereafter, the most common topologies for ac-ac, dc-dc and ac-dc interconnections have been reviewed, focusing on the specific characteristic of each of them. This revision has shown that ac-dc ICs have been studied extensively in recent years, primarily due to the increasing interest in hybrid microgrids. In addition, the development of ac-ac ICs has been significantly addressed in the literature mainly caused by the increasing interest in replacing conventional transformers by power electronic converters (SSTs). In this sense, the review has shown that the use of ac-ac ICs makes more sense as long as their dc links are employed for the integration of other systems (generation, storage or loads). Lastly, it has been observed that there are very few examples in which the interconnection of dc grids is investigated, although it will be fundamental to transfer the knowledge from the other two types to the coming dc grids. The study about the topologies has also shown that more complex ICs can be easily analysed by considering that the intermediate buses of the converter are an additional grid. In this way, two- or three-stage topologies can be decomposed as two different ICs and their controllers can be defined independently.

From all the ancillary services that ICs can provide, this review has focused on the primary regulation because it will be a mandatory service in the future converter-dominated power systems. One of the main goals and contributions of this review has been to propose a general classification for the types of primary regulation techniques for ICs, as several methods have been proposed but no classification existed in literature. Special effort has been made in developing an analysis which is valid regardless of the voltage nature and number of conversion stages, covering any kind of power converter and grid type. This means that the techniques reviewed in this paper can be directly applied at an IC no matter the characteristics of the interconnected grids. From the comparison of the primary control techniques, it has been shown that ICs can work as the classical DG or ESSs, regulating the active power of one of the grids in grid-supporting or grid-forming mode (which has been named as single grid-supporting and grid-forming mode). However, ICs do not have an established primary side as in the case of these systems and therefore their control philosophy should consider the situation of the grids they are interconnecting to improve the overall performance. In this context, it has been highlighted that ICs could consider the active power reserves of the two interconnected grids to support both grids under contingencies. This last method, defined as dual grid-supporting operation, is considered to be a more interesting approach from the perspective of the overall system, because it might help in balancing the entire primary reserve of the grid. Even though different approaches can be employed to provide this dual grid-supporting operation, the dual droop is considered one of the most interesting approaches from the analysed techniques. This approach facilitates the definition of the droop curves of each grid independently, which enables the adaptation of the controller depending on the situation of each grid. This means that the so-called single grid-supporting technique is a particular case of the dual droop strategy; in this case, one of the droop curves is disabled and the controller only responds under the perturbations of one of the grids.

In the last part of the review some potential research gaps have been included. Even though there are different IC topologies and control strategies to provide some kind of primary regulation to the system, there are different aspects that require a more thorough analysis. One of these aspects is their optimal design, sizing and location in the grid; even though there are some studies about their design (primarily for SSTs), their sizing from the system perspective is an important characteristic that almost has not been considered in the literature and there are no approaches to determine the optimal location of ICs in the power system. Another relevant aspect is the emulation of inertia via ICs to increase the inertial behaviour of grids mainly dominated by power electronic converters. Until now, the proposed control techniques only consider emulating the inertial behaviour to one of the sides of the IC, but it might be interesting to analyse whether these devices can contribute to the inertia of all the grids they are interconnecting in analogy to the dual primary regulation techniques.

Acknowledgements

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