Hybrid ac/dc microgrids—Part I: Review and classification of topologies

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Abstract

Microgrids have been widely studied in the literature as a possible approach for the integration of distributed energy sources with energy storage systems in the electric network. Until now the most used configuration has been the ac microgrid, but dc-based microgrids are gaining interest due to the advantages they provide over their counterpart (no reactive power, no synchronization, increasing number of dc devices, etc.). Therefore, hybrid ac/dc microgrids are raising as an optimal approach as they combine the main advantages of ac and dc microgrids. This paper reviews the most interesting topologies of hybrid ac/dc microgrids based on the interconnection of the ac and dc networks and the conventional power network. After performing a description and analysis of each configuration, a comparative evaluation has been performed to highlight the most important features of each one. The future trends identified during the study also show that several features such as the scalability, modelling or design require further research towards the integration of hybrid microgrids in the power network.

Keywords: distributed power generation, hybrid, microgrids, renewable energy sources, smart grids, solid state transformers, topology

1. Introduction

The dependency on fossil fuels, the constant increment of the energy consumption or the poor energy quality supplied by a conservative and aged power network, among other reasons, have led to an unsustainable energy system that requires modifications to handle these problems. According to the International Energy Agency (IEA), the total energy final consumption has increased from 6.106 Mtoe* in 1973 to 13.371 Mtoe in 2012, and an increasing tendency is foreseen, especially in developing countries [1]. Regarding the total energy share, fossil fuels—oil, coal and natural gas—shared the 81 % of the total energy consumed in 2012 [1]. These facts are causing a rapid reduction of the fossil resources that maintain the current energy system, and represent a harmful source of CO_2 emissions to the atmosphere.

In this context, great research effort has been and is being done so as to discover alternative generation methods—mainly from renewable energy sources (RES)—and suitable technologies for their integration in the power grid. Several studies have been carried out by national and international organizations to see the feasibility of a purely renewable energy sector in the following decades [2]–[6]. However, this energy model presents several challenges that need to be further researched.

The previously mentioned higher consumption levels (which are also reflected in the electric grid) and the considerable ageing of the power network lead to a less efficient utility grid. According to the IEA, the total worldwide power losses in the transmission systems of the power grid were approximately the 8 % in 2011 [7].

The integration of RES is an attractive solution to deal with these problems, but the adaptation of the utility grid to integrate them in a distributed, efficient and reliable manner without excessive investment still remains a challenge—the installed capacity of distributed generation (DG) is expected to double by 2023 [8]. Among the solutions proposed, the introduction of the smart grid concept is envisioned as one of the most attractive approaches [9]–[16]. It is expected that in the following decades the electric market will suffer a similar evolution to the one of Internet in the twentieth century, leading to the concept named Energy Internet [17] or Enernet [18].

Microgrids, which are small-scale smart grid types, are one of the most attractive solutions to improve the power flow in distribution networks and reduce power losses in transmission lines by interconnecting distributed generation, energy storage systems (ESS) and loads in the same grid [19]–[25]. Several reviews can be found where different aspects of these networks are studied: control strategies [26]–[33], [21], [34]–[36], [23], [37]–[39], test beds around the world [23], [19], [25], [40], optimization techniques and available software tools [41]–[46], protection devices [32], [37], [39], [47], [48], etc.

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[*] The unit Mtoe refers to Million tons of oil equivalent, widely used to express high quantities of energy (1 toe equals to 41.868 GJ or 11.63 MWh).

Regarding the topologies of microgrids, they can be divided in three mayor groups, namely ac, dc and hybrid [23], [39], [40], [49]–[56].

AC microgrid is the most used configuration as it provides a direct way to integrate DG units in the current utility grid with minimum modifications. This architecture is characterized for facilitating the modification of voltage levels with low frequency transformers and for having high fault management capability—i.e. detecting and handling the faults—with a wide range of protection devices. However, it presents some drawbacks such as the need of synchronization of DG units or the circulation of reactive power that increases the power losses in the transmission system. The feasibility for the integration of ac microgrids has been widely studied in the literature [19], [24], [40], [50].

Even if most distribution networks operate in ac, the high penetration of dc-based DG units, ESS units and loads, among other features, is opening the doors for dc operated distribution networks. Their main advantage is a higher overall efficiency as less interface converters are used and there is no circulation of reactive current in the network. Moreover, there is no need for synchronization of DG units. On the other hand, this configuration requires a high modification of the current distribution network and consequently the cost increases drastically. Several studies can be found which depict the benefits of these configuration over their counterparts [22], [23], [39], [50], [53], [54].

Hybrid ac/dc microgrid configurations are causing great interest as they combine the advantages of ac and dc architectures [52], [53], [22], [51], [55]. Their main characteristic is that the two networks—ac and dc—are combined in the same distribution grid, facilitating the direct integration of both ac- and dc-based DG, ESS and loads. This feature provides an efficient way for the integration of upcoming RES or electric vehicle (EV) units with minimum modifications of the current distribution grid, reducing the total cost.

Although hybrid ac/dc microgrids are a great solution for the integration of smart grids in the conventional distribution network, there are very few papers that cover their development as the greatest part of the research focuses on ac or dc systems independently. Some studies can be found where the main characteristics of ac and dc microgrids are compared, as in [22], [23], [39], but the hybrid approach is not considered in these comparisons. Consequently, there are almost no studies related to the architectures or the topologies of these networks. Therefore, the aim of this paper is to perform a comprehensive review and classification of the most interesting topologies for hybrid ac/dc microgrids found in the literature. This study depicts and compares the most important characteristics of each topology, helping researchers and developers in the design of future hybrid microgrids.

Initially, a brief overview of hybrid microgrids is performed in Section 2, stating their most important advantages and disadvantages. Section 3 collects a wide literature review related to the most used architectures, where the topologies are classified depending on their connection to the power grid. In addition, a discussion part is presented where the main characteristics of each approach are compared. Finally, in Section 4 and 5 the future trends and main conclusions identified during the study are collected.

2. Hybrid microgrid overview

Hybrid ac/dc microgrids are one of the most interesting approaches towards the development of the smart grid concept in the current distribution network. A typical hybrid microgrid structure is shown in Figure 1, where the ac and dc networks can be distinguished. Several devices can be observed in the diagram: DG and ESS units, a diesel generator, variable speed drives (VSD), ac and dc loads, etc.

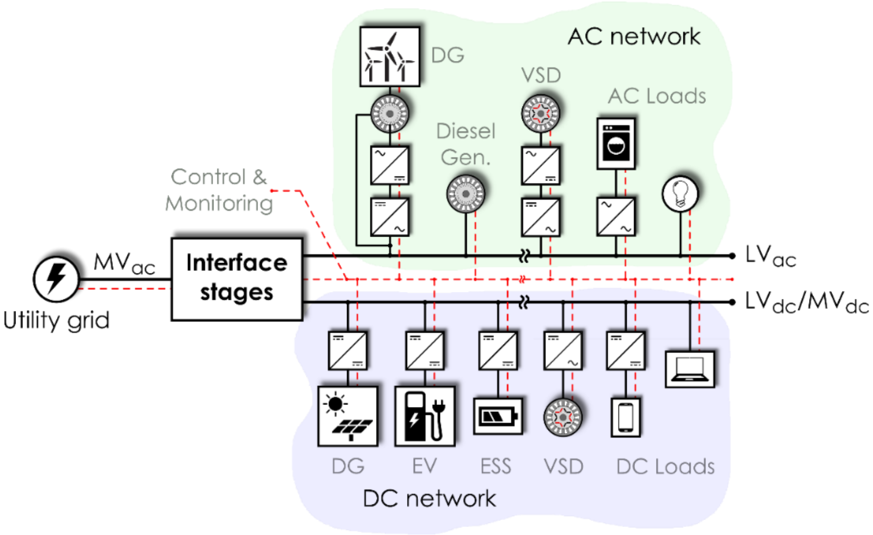


Figure 1 – Example of a hybrid microgrid configuration.

The most important advantages of these microgrids are:

- **Integration:** ac- or dc-based devices are directly connected to the network with the minimum number of interface elements, reducing the conversion stages and therefore the energy losses. This feature makes hybrid microgrids suitable for the integration of the increasing dc-based units—e.g. EV, photovoltaic generation, fuel cells, ESS, laptops, mobile phones, etc.—while maintaining the ac-based devices connected to the ac network.
- **Synchronization:** there is no need for synchronization of generation and storage units as they are directly connected either to the ac or dc network. Hence, the control strategy for this devices is simplified.
- **Voltage transformation:** the modification of voltage levels can be performed in a simple manner in the ac-side by the use of transformers. In the dc-side the conversion is performed by the use of dc-dc converters.
- **Economic feasibility:** a hybrid microgrid can be developed by the addition of a power converter to the current distribution grid and the communication network for the connected devices. This makes the overall cost higher than ac microgrids because of the main power converter. However, if the number of attached devices increases, the investment will be returned faster as the number of total interface converters is reduced.

On the other hand, this architecture presents various drawbacks that need to be further researched:

- **Protection:** a wide variety of protection devices can be found for ac-based networks, as they have been widely studied and used in the current utility grid. However, dc protection devices have not been researched so deeply. Moreover, fault detection is performed in a more simple way in ac networks thanks to the zero-crossings of the current, whereas this method cannot be used in dc grids.
- **Reliability:** reliability of hybrid microgrids is lower than in ac ones as an interface power converter is introduced in the distribution network to generate the dc-link. However, the reliability of the connected devices is improved as the number of converter stages is reduced.
- **Control complexity:** the management of hybrid microgrids is more complex than in its counterparts. This is because it is necessary to perform the control of the devices attached to the ac and dc networks and the interface power converter between them. Therefore, stable and reliable power supply has to be ensured for both networks, and this task becomes challenging especially when the microgrid operates in an autonomous or islanded mode. The issues concerning control strategies are discussed in the second part of this paper [108].

3. Hybrid microgrid architectures

Several network configurations can be found in the literature, which are distinguished by the connection with the utility grid or the structure of the inner current conversion stages. As it can be observed at Figure 1, two main groups can be identified for the interface devices placed between the ac, dc and the utility network: coupled ac and decoupled ac configurations.

At coupled ac topologies the ac network of the microgrid is directly connected to the power grid by a transformer and an ac-dc converter is used for the dc network. Alternatively, decoupled ac configurations are composed at least by an ac-dc and dc-ac stage; this means there is no direct connection between the power grid and the ac network of the microgrid. Figure 2 shows the most important configurations identified for both topologies.

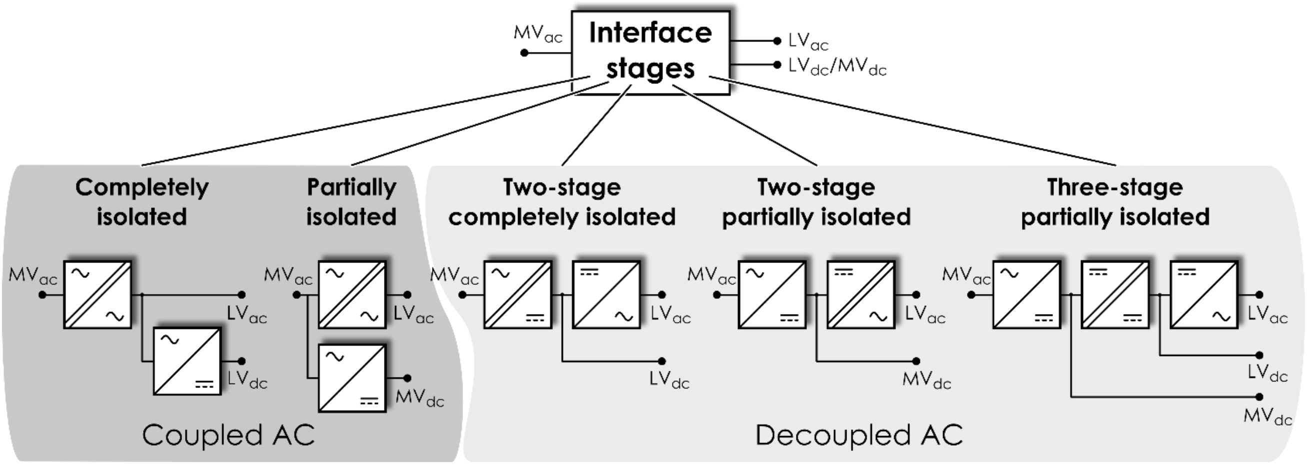


Figure 2 – Hybrid microgrid architecture classification.

In the following sections a deeper analysis of these configurations can be found.

3.1. *Coupled ac microgrids*

The main feature of this configuration is that the ac network is directly connected to the power grid by a transformer. The advantage is that the ac network of the microgrid is fixed by the utility grid in normal operating mode. In addition, the development of a coupled ac microgrid is less expensive than the decoupled one. This is due to the smaller size ac-dc converter that is needed to handle the power flow between the utility grid and the dc network.

Two principal methods have been found for the arrangement of conversion stages in coupled ac microgrids. In the first case, as it can be seen in Figure 3, a transformer is located at the point of connection with the power network. This provides galvanic isolation to the entire microgrid, and reduces the voltage level so that LV ac and dc networks are generated.

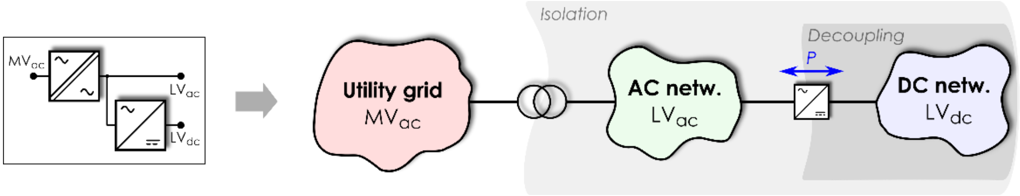


Figure 3 – Coupled ac, completely isolated hybrid microgrid configuration.

On the other configuration (Figure 4), the ac-dc converter that generates the dc microgrid is directly connected to the utility grid, instead of being after the power transformer. Consequently, the rated power of the transformer is lower than in the previous approach, as it has to handle the power flow of the ac network. However, this means there is no galvanic isolation for the dc network of the microgrid, unless a second transformer is integrated.

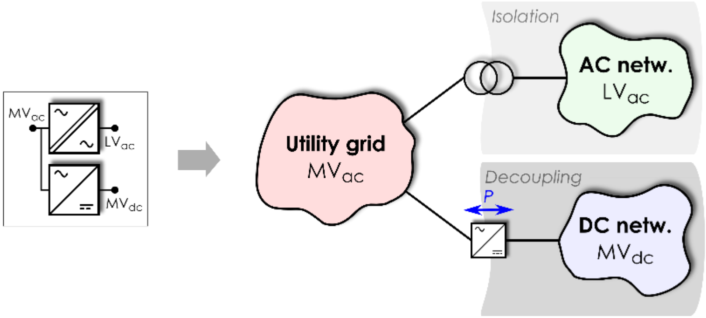


Figure 4 – Coupled ac, partially isolated hybrid microgrid configuration.

In the case of coupled ac hybrid microgrids with entire isolation (Figure 3), Jiang *et al.* proposes a hierarchically configured microgrid with both ac and dc links [51]. The architecture is divided in three main levels: micro-source level, where the dc-link, DG and ESS units are located; combo-source level, where the ac-link and the inverter for the connection between links is placed, and the microgrid level, where the interconnections of the lower level facilities and the power network are performed. According to the authors in [51], this architecture improves the flexibility and reliability of the distribution network over conventional configurations. Moreover, a plug-and-play based system is provided, which is beneficial for the integration of upcoming generation, storage or load devices [51].

Although this topology is suitable for the integration of DG units in the power grid, not all the capabilities of hybrid microgrids are used—i.e. the number of interface converters is not optimized as ac-based DG units are connected to the dc-link instead of the ac-link. A more efficient approach would be to directly connect these generation units to the ac-link of the network.

A similar approach is proposed by Goel *et al.*, who present a hybrid microgrid capable of managing the power flow in two directions (consumption/generation) by the utilization of a bidirectional ac-dc converter [55]. The grid-tied and autonomous modes of operation are briefly explained. In the first operating mode, the authors state that DG systems operate in maximum power point tracking (MPPT) and the utility grid acts as an infinite capacity energy storage—therefore the use of distributed ESS can be avoided. In the second mode, there is no link with the power network and the bidirectional ac-dc converter manages the power flow between the ac- and dc-link. In this case, DG units operate in MPPT mode or link regulation mode, depending on the requirements.

Hosseinzadeh and Salmasi have also employed this topology for an islanded hybrid microgrid in [57] and [58]. In this paper, they propose a power management architecture that optimizes the use of renewable resources, minimizes the usage of fuel-based generator, extends the lifetime of the batteries and limits the utilization of the main interface converter between the ac and dc micro-grids. The results show the feasibility of this topology for the integration of ac- and dc-based distributed devices in the power network.

This topology can be seen in another type of application studied by Nutkani *et al.* in [59], where the interconnection of two LV ac microgrids is proposed. In this approach the use of the dc network is limited to manage the power flow between both ac microgrids, but it could be employed to integrate dc-based devices in order to reduce the number of converters. This would improve the flexibility of the system as well as increasing its efficiency. The approach in this study is similar to the configuration observed in Figure 6b. However, the main difference is that in this case the ac network between the utility grid and the dc network is also a microgrid that is not decoupled from the utility grid.

The advantages presented in this configuration have caused many authors to use it in their research [49], [51], [52], [60]–[71].

Regarding the second configuration in coupled ac microgrids (Figure 4), it is usually employed for the interconnection of several asynchronous ac networks (Figure 5). An example of a microgrid with direct connection between the dc network and the power grid is studied by Baradar *et al.* in [72], where an embedded dc network inside the ac utility network is proposed. In this case, the connection of the dc network is performed by a multi-terminal high-voltage dc converter (MTDC), although the same concept could be applied for low voltage applications. According to the authors, this connection can work in two modes: (1) ac grid with an embedded dc grid via the MTDC converter, (2) connection of asynchronous ac grids by the dc-link of the MTDC converter. In this application the dc network is linked via ac-dc converter to the power grid, so no galvanic isolation is present.

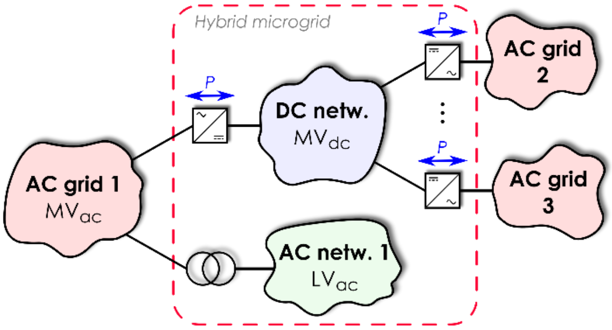


Figure 5 – Example of a coupled ac, completely isolated hybrid microgrid for the connection of several asynchronous ac networks.

This type of configurations are not as common as the ones observed in Figure 3. One of the main reasons is that protection devices for dc-based MV networks are not so common and their price is relatively high. The most typical applications for this topology are remote or large scale photovoltaic or wind farms, where the energy is transmitted via a dc-link from the generation point to the connection point with the utility grid [73]. However, these applications are mostly independent dc microgrids and the combination with ac-based ones is not performed. Besides that, MV dc networks are rarely used in microgrids nowadays, so the number of applications with this configuration are very low.

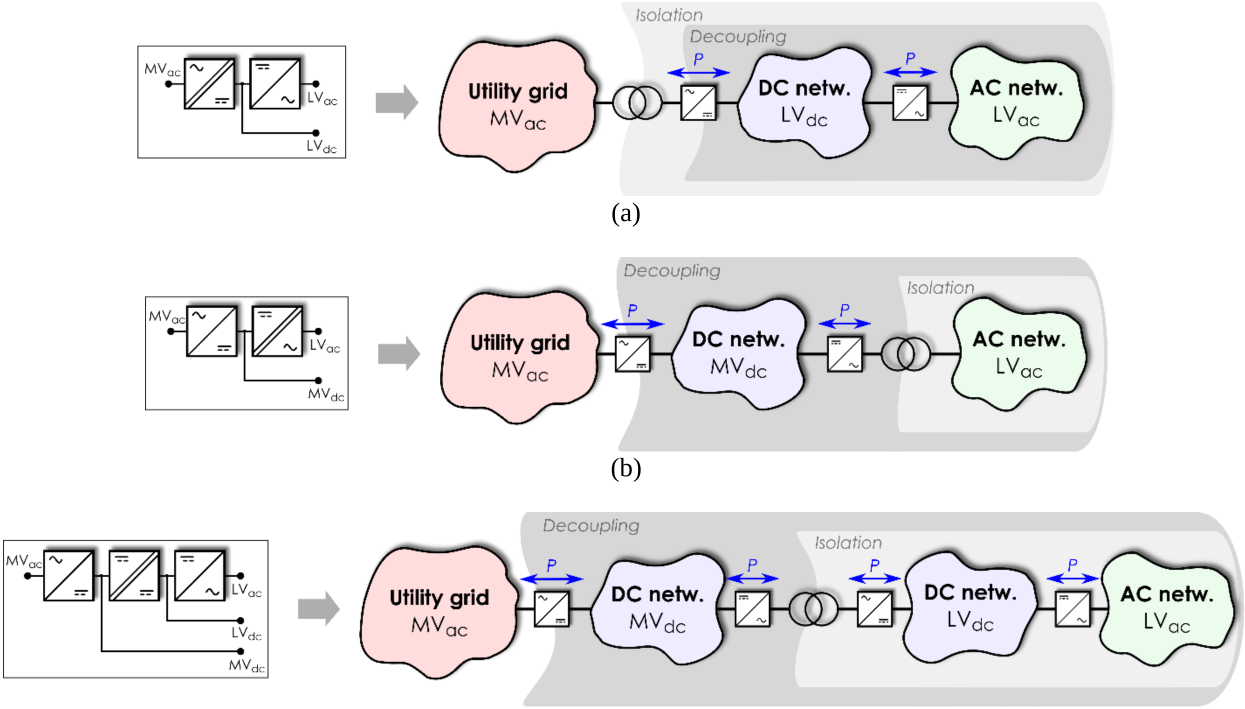
3.2. Decoupled ac microgrids

This type of configuration is gaining interest in the last decade due to the advantages it provides over coupled ones. Firstly, the ac network of the microgrid is decoupled from the utility grid by a dc stage, what provides fault isolation and independent control strategies for both sides of the microgrid. Moreover, the power flow monitoring and control of the microgrid is inherent of the interface device, which is useful for the coordination with upper level control platforms such as the supervisory control and data acquisition (SCADA) systems managed by electric companies.

In order to develop the configurations under this category, the integration of solid state transformers (SST) is envisioned as one of the most promising alternatives [74]–[78]. The key feature of these devices is that they can directly replace the current passive transformers while enabling management over the power flow. Moreover, they ensure decoupling between the power grid and power network, and provide a dc-link that is necessary for the development of a hybrid microgrid. These devices are suitable mainly for traction and distribution grid applications. She *et al.*, for example, study the integration of SSTs in microgrid environments, where their feasibility to work both in grid-tied and islanded mode is demonstrated [79].

SSTs are composed by staged power transformers and can be arranged in numerous configurations. However, three architectures that cover the most important SST topologies have been identified in the studies carried out in [75], [77], [78], [80], [81]: two-stage SST with LV dc network, two-stage SST with MV dc network and three stage SST network with LV and MV dc networks (Figure 6a, b and c, respectively).

The differences between the three configurations reside in the location of the transformer and the stages of the converter. In the first approach (Figure 6a), the transformer is located at the input of the SST, providing galvanic isolation to the entire microgrid. However, in the second configuration (Figure 6b), this transformer is placed at the LV ac network, which ensures isolation for this grid uniquely. Finally, in the third approach (Figure 6c), a dc-dc stage is introduced where a high frequency (HF) transformer is installed. This provides isolation for the LV ac and dc networks, while enabling a MV dc-link.



(a)

(b)

(c)

Figure 6 – Hybrid microgrid with decoupled ac network: (a) two-stage completely isolated configuration, (b) two-stage partially isolated configuration and (c) three-stage partially isolated configuration.

Regarding the first approach (Figure 6a), several studies can be found in the literature [75], [82]–[87]. Karabiber *et al.*, for example, propose a solution for the integration of DG units by the use of an energy conversion station [82]. According to the authors, this approach avoids the problems that appear when integrating DG units in the conventional ac grid—e.g. stability or synchronization issues. Moreover, it supposes no additional cost for conventional grid consumers in microgrids. A similar approach is studied by Majumder in [83], where the integration of DG and ESS systems is performed by a back to back converter with a middle dc-link. The solution is validated and it is concluded that the system operates reliably with various DG units.

On a similar approach, Radwan *et al.* study the behavior of a voltage source converter-interfaced hybrid microgrid with attached generation, storage systems and loads [87]. The aim of the paper is to analyze the stability of the network taking into account the regulation of the interface converters. The authors conclude that the stability of the system is negatively affected by the tight regulation of these converters, although they state that with the inclusion of active compensators the stability requirements are fulfilled. This study shows that the employed topology is a feasible solution towards the integration of distributed nature devices.

Another solution related to the configuration shown in Figure 6b is presented by Sabahi *et al.* in [88]. In this approach, an ac-dc stage is introduced to provide the dc network, and afterwards a dc-ac converter is included with a high frequency transformer for isolation and a cycloconverter that determines the output voltage sign. Although the voltage levels in this solution are all of LV, the same approach could be developed for MV to LV conversions, as has been studied by Banaei and Salary in [89]. This topology, as in the topology observed at Figure 4, is not as common as the rest of configurations. Among other reasons, the protection device family for MV dc applications is very limited, and the use of a LV dc stage for the decoupling of the ac microgrid is a more feasible solution because the design of the interface converter is simplified.

Even if two-stage solutions are the most simple approach for the generation of the dc network in terms of conversion stages, the three-stage topology (Figure 6c) is one of the most studied approaches in the literature due to the advantages it presents [74]–[76], [81], [85], [86], [90]–[103]. Among other features, this architecture provides MV and LV dc networks in addition to the LV ac one. Moreover, even if this topology employs a MV dc stage as in the previous solution (Figure 6b), the use of a medium frequency (MF) transformer in the dc-dc stage provides galvanic isolation of the LV-side of the microgrid and drastically reduces the size of the device. These features make this configuration suitable for the integration of small- or high-scale DG, ESS or loads even if galvanic isolation is not provided for the MV dc network.

The optimal design of three-stage SSTs has gained a lot of strength in the last decade and therefore is one of the main research areas nowadays. Therefore, some of the main purposes of researchers are to improve the efficiency and reliability while reducing the size and cost of the device.

In this context, Huber and Kolar have researched the feasibility of three-stage SSTs over passive distribution transformers in terms of volume, weight, losses and material costs [76]. In this study, the authors compare a 1000 kVA distribution transformer with an equally rated SST. They outline that the latter is less optimal in terms of cost and efficiency, but the volume and weight of the device is considerably reduced. When the SST provides half of the rated power in the ac network and the other half in the dc network, a reduction of approximately the 50 % and 60 % are observed in the volume and weight, respectively. Regarding the rest of the parameters, it is concluded that the cost increases by a factor of two while little reduction of the efficiency takes place.

The use of a three-stage SST is also studied by Zhao *et al.* in a hybrid ac/dc microgrid [104]. Simulation as well as experimental tests are carried out in order to validate the operation of the converter under different conditions. The results show a good performance of the converter with efficiencies above 90 %, which corroborates that the use of this kind of interface device can be competitive against conventional distribution transformers.

This same topology can be observed in the study performed by Zhang *et al.* in [105], where a control strategy is proposed in order to mitigate the circulating currents between the three-stage SSTs.

Although most approaches based on this topology employ the dc and/or ac networks for the integration of devices, there are other microgrid applications employing this topology. One example can be seen in [74], where Falcones *et al.* propose that the distributed generation and storage devices are connected via the MF transformer of the SST. Simulation and experimental results show a good performance of the proposed topology and control strategy.

One of the key factors of three-stage SSTs is the development of the dual active bridge (DAB) for the dc-dc stage of the converter [75], [81], [85], [90], [97], [98], [100]. According to the authors, this topology offers a good balance between control flexibility/efficiency and system complexity. In order to observe the benefits and drawbacks offered by different SST configurations, Falcones *et al.* carry out a comparison between six topologies [75]. In this evaluation, the circuits are analyzed and simulations are performed. The final conclusion is that the three-stage offers the most simple approach while providing galvanic isolation, bidirectional power flow and decoupling from the utility grid, among other features.

On a similar approach, Qin *et al.* study the behavior of a DAB-based dc-dc converter with a phase shifted modulation (PSM) strategy both in simulation and experimental tests [86]. The results show efficiency values over the 90 % for rated power operation.

Regarding the development of DAB converters, Ortiz *et al.* state that one of the most challenging tasks resides in the design of the MF transformer [81], [99]. The studies propose suitable transformer designs and optimal frequencies to take advantage of the transformer characteristics.

The design of interface power converters present other challenges such as serialization of power semiconductors due to their low blocking voltage capabilities. In order to face this issue the modularization of power converters is usually studied. This might reduce the size and therefore increase the power density of the device. In addition, it provides relatively simple scalability capability by adding parallel or series converter branches. Several authors have studied this feature for some of the previously presented topologies [75], [77], [78], [80], [81], [85], [92]–[94], [101], [102], [104].

Kolar and Ortiz perform an extensive review of the degrees of freedom regarding the modularity of converters [77]. In this study, they propose a classification methodology that is used afterwards for the description of various modular topologies used in the literature. As it can be observed in the study, the degrees of freedom in the modularization of SSTs are the number of series/parallel cells, power conversion partitioning and phase modularity. Although the modularization is one of the most interesting research fields regarding interface converter topologies this characteristic is not analyzed in detail as it is out of the scope of this paper.

3.3. Discussion

As has been stated during the paper, each configuration provides certain features that make them suitable for specific applications. In order to highlight the main characteristics of each topology, in this chapter a comparative evaluation is carried out.

Below the most relevant features that are used in the comparison are explained:

- **Isolation:** the level of galvanic isolation between the microgrid and the utility grid is evaluated with this parameter, stating in each case the sides of the microgrid that covers this isolation.
- **Volume:** the volume of the interface devices (transformers and power converters) connecting the microgrid and the main power network are compared. Converter-based devices require a lower volume than the ones based on transformers.

- **Cost:** this variable takes into account all interface devices for the generation of the ac and dc networks of the microgrid. If the stages are converter-based, the cost of the device increases due to the number of components. In contrast, the knowledge over power transformers make them very cheap for this type of applications, as they are easy to construct and do not require any control or exclusive maintenance.
- **Maintenance:** the level of maintenance of each system is approximately compared, based on the number of power conversion stages. The devices with more electronic converters will require more maintenance.
- **Reliability:** similar to the maintenance of the system, reliability is compared based on the number of power conversion stages and the number of electronic converters.
- **Scalability:** in this case, the capability for load-dependent voltage level variation is considered. Power converters can be parallelized or serialized in a simple way and online depending on the instantaneous power flow, which increases the overall efficiency and reduces the ageing of the components. However, transformers require additional devices to provide this feature (e.g. tap changers, etc.).
- **Modularity:** the capacity for increasing the rated power of the conversion stages is compared by this variable. New branches can be added to the original power converter in parallel or series to increase their rated power. In order to perform the same variation with transformers, new units need to be added in parallel for operating at higher rated power levels.
- **Controllability:** depending on the type of stages of the main power converter, the control capabilities over the ac and dc networks and the power flow between them varies. The interface stages that contain exclusively converters will have higher control capabilities although the complexity of the control strategy will also increase.
- **Fault management:** when a fault occurs on either side of the microgrid, the interface converter can react and isolate the faulty part. Depending on the stages of this converter, the isolation can be performed for the entire microgrid or partially.

Table 1 collects the features of the hybrid microgrid architectures in terms of the aforementioned characteristics.

Table 1 – Comparative evaluation of hybrid microgrid configurations

	Coupled ac		**Decoupled ac**		
Feature	Completely isolated	Partially isolated	Two-stage completely isolated	Two-stage partially isolated	Three-stage partially isolated
Galvanic isolation	Complete	AC network	Complete	AC network	AC & LV DC networks (not the MV DC network)
Volume	High	Medium	High	Medium	Low
Cost	Low	Medium	Medium	High	High
Maintenance	Low	Low	Medium	Medium	High
Reliability	High	High	Medium	Medium	Medium
Scalability	Low	Low	High	High	High
Modularity	Low	Low	High	High	High
Controllability	Medium	Medium	High	High	High
Fault management	Medium	Medium	High	High	High

The comparison shows that the maintenance and cost are higher for the decoupled ac topologies and their reliability is not as good as the transformer-based alternatives. However, their scalability and modularity are higher and the volume of the devices is lower in most of the cases. This makes them suitable for the development of hybrid microgrids as they provide high upgrading capabilities—which is necessary for the upcoming DG and ESS systems—as well as power flow management and isolation. Moreover, these topologies can actively perform the fault management for the entire microgrid.

4. Future trends

Although several works focus on ac and dc microgrids and their configurations are relatively simple, hybrid microgrids present several challenges that do not appear in the others. This section collects the most important future research topics that have been identified for the development of hybrid microgrid topologies.

On the one hand, hybrid microgrids are scalable and therefore their implementation can be performed at various levels and in several configurations. Their integration could be performed on a MV distribution network or on a LV residential environment. However, there are no studies where the architecture of these systems is analyzed at these scenarios. Although several optimization techniques can be found for microgrid systems [41]–[46], the adaptation of these techniques is a field that needs to be researched more deeply.

The modeling of hybrid microgrids is also envisioned as an interesting approach as there are very few studies that cover their entire characterization. Under this topic power flow analysis is one of the most interesting approaches, as well as small- and large-signal models [64], [106]. These models would provide a versatile tool for the analysis and comparison of the topologies for hybrid ac/dc microgrids at conditions of real systems, improving their development and industrialization.

On the other hand, as mentioned during the paper, the development of power interface converters still remains a challenge. Some studies have been found where the analysis of these devices is performed, but they have not been thoroughly studied under microgrid scenarios. Moreover, the design of this devices is also a hot topic in the literature to improve their performance: control strategies that regulate the power flow between networks while ensuring proper power sharing, improvement of the reliability and efficiency, reduction of their overall cost, etc.

Dual active bridge based converters have been identified as a feasible solution for the implementation of SSTs at hybrid microgrids, but the design of the medium frequency transformer of this converter is also an interesting approach that is already being studied and will continue developing in the near future [99], [107].

Related to the design of power converters, their modularization is also one of the key topics that needs further research [77], [81]. Depending on the application and the input and output voltage levels of the microgrid, the configuration of the device varies and different approaches need to be developed. The use of a modular converter provides a highly scalable device that can be adapted to several applications, thus providing a very flexible system. On a distribution network that increases the connected devices, for example, it would be necessary to replace the LF transformer by another that has a higher rated power. Another solution would be to oversize the transformer when building the distribution station so that it can handle a high number of devices, but this would mean a higher cost in the installation. However, modular SSTs can be sized according to the number of devices on the initial stage of the design and increase their rated power by adding additional modules to the converter when it is required.

5. Conclusions

Microgrids are envisioned as an attractive solution towards the integration of DG units in the utility grid. This solution will bring a reduction in the fossil fuel dependency and an increment in the efficiency of the overall electric grid.

Although most of the studies performed in the literature mainly focus on ac and dc microgrids, hybrid ac/dc systems are an interesting solution as they combine the advantages of the previous two configurations. This paper has described and analyzed the most important characteristics regarding the topologies of hybrid microgrids.

After performing an overview of the most relevant advantages and disadvantages of hybrid ac/dc microgrids, a classification of the most used topologies has been carried out, based on the interconnection type of the ac and dc networks and their connection to the power network.

In this context, two main groups have been distinguished, which are named as coupled ac and decoupled ac configurations.

Regarding coupled ac architectures two approaches have been identified: the completely isolated topology and the partially isolated topology. As it has been previously discussed, the configuration that includes a full-size power transformer and an ac-dc converter has some interesting features: it provides galvanic isolation for the entire microgrid and the ac-dc converter has a smaller size than its counterpart, as it only has to handle the power flow between the ac and the dc network.

On the other hand, under the decoupled ac category, three topologies have been distinguished: the two-stage completely isolated configuration, the two-stage partially isolated one and finally the three-stage partially isolated configuration. After studying and comparing the three approaches it has been observed that the three-stage converter topology under this category presents several advantages: with this system three networks can be used for the integration of the devices of the microgrid (low voltage ac and dc and medium voltage dc), galvanic isolation is ensured for the ac and dc LV networks and full power control capability is provided.

In order to highlight the most relevant features of each configuration a comparative evaluation has been carried out, showing that there is not an optimal solution for all the applications. The configuration of the hybrid ac/dc microgrid will highly depend on the application and environment it is going to be integrated (market conditions, regulatory conditions, feasibility for the integration of DG units, etc.), so a deeper research of the scenarios and topologies is considered necessary.

The authors consider that this paper provides a guide for developers to further research the development of hybrid microgrids at power distribution applications. Among the factors that need to be improved, the reliability, efficiency and cost of the interface device are considered to be some of the most important ones for the integration of these microgrids in the power network.

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