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Chapter

A Review on the Driving Forces, Challenges, and Applications of AC/DC Hybrid Smart Microgrids

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Abstract

The majority of Medium Voltage (MV) and Low Voltage (LV) power systems are based on and operate using Alternating Current (AC) infrastructures. Yet, modern energy market needs, which promote more decentralized concepts with a high Renewable Energy Sources (RES) penetration rate and storage integration, bring Direct Current (DC) to the forefront. In this sense, AC/DC hybrid smart microgrids constitute a newly-introduced research field with a variety of potential applications that combine the benefits of both AC and DC systems. The purpose of this chapter is to review the advantages and disadvantages of AC/DC hybrid grids and analyze potential applications that would benefit from such infrastructures. Also, the most significant efforts and requirements for the constitution of a solid regulatory framework for AC/DC hybrid grids are presented, to pave the way towards their wider adoption by the market.

Keywords: AC/DC hybrid microgrid, microgrid applications, medium voltage, low voltage, framework

1. Introduction

Electrical grids, from the early stages of their implementation up until the past few decades, have been traditionally based on the energy generated from fossil fuels, such as coal, oil and natural gas [1]. As a result, and taking into account the technological expertise and the available technology at the time they were developed, most architectures were designed to be centralized. Moreover, the overall energy system architecture had a unidirectional approach, from centralized units of production to dispersed customers based on Alternating Current (AC) transmission and distribution networks, a process that has not been friendly to the environment [2].

Yet, the modern socioeconomic requirements and the need to take effective actions for the protection of the environment are challenging the traditional approach of electrical grid architectures [3]. The need for sustainability in the energy sector,

underpinned by the recent technological developments, has led to the development of distributed, environmental-friendly and predominantly DC-based power supply system's [4]. Such systems typically include photovoltaic (PV) panels, Battery Energy Storage Systems (BESS), fuel cells, etc. [5]. This type of Distributed Energy Resources (DER) is most efficiently incorporated in smart microgrids [6]. Smart microgrids constitute advanced architectures, the key elements of which are smart sensors, advanced metering infrastructures, information technologies, Internet of Things (IoT), Cloud of Things and real-time communication systems. In this way, they enable the digitalization and decentralization of the grid, thus allowing for the efficient and seamless Renewable Energy Sources (RES) integration, the management of multiple distributed power supply units, the bidirectional power flow and a variety of grid-flexible services, such as black-start, island-mode operation and congestion management [7]. Furthermore, since many of the DER and some loads utilize DC power, research is oriented towards the design and development of AC/DC hybrid smart microgrids [8]. The structural differences between the traditional AC electrical grid and the AC/DC hybrid smart microgrid are presented in **Figure 1**.

This chapter aims to review the motives and applications of AC/DC hybrid smart microgrids. For this purpose, it is structured as follows: the driving forces for the development of AC/DC hybrid smart microgrids are analyzed in Section 2, their possible applications are analyzed in Section 3, the challenges regarding the regulatory framework for their wider adoption by the market are presented in Section 4, and finally conclusions are summarized in Section 5.

Figure 1.
Main differences between past AC and modern AC/DC hybrid smart microgrid architectures.

2. Driving forces and challenges for the development of AC/DC hybrid smart microgrids

The integration of DC systems in AC-based infrastructures provides a new framework of grid capabilities [9]. As it is foreseen, DC solutions need to “harmoniously co-exist” with the already available AC infrastructures, developing hybrid architectures in which the best result of both approaches can be achieved [10].

In this manner, AC/DC hybrid smart microgrids bring a new perspective into a variety of applications [11]. As opposed to the traditional AC infrastructures, some of their main advantages include:

- **Efficient integration of DER and reduction of primary energy consumption** [12, 13]: A majority of RES and storage systems utilized produce DC power, which would be more efficiently deployed in a DC grid instead of an AC grid, rather than having to undergo DC/AC and AC/DC conversions reducing efficiency. Typical examples are considered to be PVs, BESS, fuel cells or even EVs which may be used as additional storage, in vehicle-to-grid (V2G) mode [14]. More specifically, in a DC grid, these sources’ supply is not required to be converted from DC to AC. Contrariwise, instead of DC/AC inverters, DC/DC converters need to be installed [15], as presented in **Figure 2**, which have better efficiency and a smaller size and volume. Furthermore, wherever it is necessary, bidirectional DC/DC converters can be employed, for example in the case of BESS. As a result of the above, the RES generation is exploited to the maximum, the primary energy consumption is reduced and potentially required space is reduced [16].
- **Efficient integration of DC loads** [17]: The distribution of DC power (instead of AC) to DC loads may result in energy savings from the point of view of the end-users. By eliminating the conversion from AC power to DC power with the use of the respective AC/DC inverter, as presented in **Figure 2**, the associated losses are reduced, resulting in lower electricity bills. This modification has the potential to lead to substantial cost savings especially in the case of DC loads such as computer data centers (which predominantly use DC power for their electronic equipment), EVs and EV charging stations, Light Emitting Diode (LED) equipment, etc. [18].
- **Power transmission over long distances** [19]: Considering the effectiveness of high and medium-voltage DC lines, more power may be transferred over

Figure 2.
 Efficient integration of DC power supply and DC loads in AC/DC hybrid smart microgrids.

long distances, compared to their AC counterparts, owing to less severe stability issues. This feature makes DC integration into already existing AC grids extremely valuable for the future expansion of the grid and the connection of remote loads (such as in islands or isolated locations) or remote RES installations [20]. Major technological developments have enabled the increase of DC operating voltage levels in the order of kV, allowing efficient and reliable power transfer even for distances in the order of several thousands of kilometers.

- **Power quality enhancement** [21]: DC connections can enhance the power quality of weak grids, as they provide a type of isolation “firewall” that prevents the propagation of disturbances, as depicted in **Figure 3**. In particular, the conversion from AC to DC power decouples the AC part of the grid, so that the remaining infrastructure can cope with undesirable resonances which would otherwise impose a threat in its stability and robustness. A typical example of such cases is AC harmonic oscillations, frequency instability and low inertia, which AC grids may face, due to the existence of inductive and capacitive elements, etc. In this sense, AC/DC hybrid smart microgrids present a clear advantage, especially when it comes to the connection between two AC grids with the use of DC sub-systems. Furthermore, the DC connection enables the effective integration of AC systems operating with different voltage/frequency levels.

Figure 3.
DC connections prohibit the propagation of disturbances.

- **Reduction of visual impact** [22]: Since DC lines carry only active power and have no skin effect, less current capacity is required and the necessary distance between the conductors can be reduced. This, in combination with the fact that fewer lines are required than in the respective AC systems, results in a smaller size of DC towers. The smaller size of DC towers, compared to the size of AC equivalent structures, is considered to be an advantage of DC grids. This attribute, however minor it may seem, is quite beneficial considering overpopulated areas such as cities or places where the visual impact of the grids should be minimized, such as in tourist attractions, monument areas, preserved ecosystems, etc.

On the other hand, AC/DC hybrid smart microgrids have certain drawbacks. DC technologies and the connection between AC and DC technologies have not been thoroughly studied as the common AC grids. This is attributed to the fact that the entire concept of electrical energy production, transmission and distribution has been built on AC technology, which has provided the means to progress and develop simple and cost-effective AC equipment over the years.

In this context, the implementation of DC solutions has certain disadvantages such as the lack of specific standards [23]. For a newly-introduced system, such as the AC/DC hybrid grid to establish its case against the traditional AC “status quo”, the definition of certain parameters needs to be specified. Since AC/DC applications are not as well-known and commonly used as AC applications, there is a general lack of standardized practices regarding their design and operation. This issue needs to be addressed, for the AC/DC hybrid grids to effectively enter the worldwide market.

Also, there is difficulty regarding the integration of DC systems into existing AC grids, to form AC/DC hybrid grids. More specifically, AC technologies have a simple design that has been studied and developed for many decades and is well known to grid developers and system operators. On the other hand, fewer specialists have studied DC technologies to that extent [24]. As a result, the incorporation of DC solutions to the existing grid bears difficulties in comparison with the application of AC solutions. In simple words, AC and DC systems have different starting points: the AC technology is proven and mature, whereas DC technology is in a developing process to be established, considering that power electronics converters started being utilized in the last quarter of the past century.

This is also reflected in protection and safety apparatus [25]. Once a new system is proposed, protection issues including switches, grounding and fault management systems need to be studied and established. In the case of AC/DC hybrid grids, there are protection issues that are not only related to the lack of standards but also the very nature of DC current. To be more specific, breaking a DC circuit is considered to be more difficult than the respective AC circuit because there is no natural zero crossing of the current to minimize the arc effect. For this purpose, major research efforts are carried out for the development of switchgear that can accommodate the secure disruption of DC voltages in the order of kVs, to enable the safe and reliable development of AC/DC grid infrastructures.

Furthermore, the point of common coupling between the AC and DC parts of the AC/DC hybrid smart microgrid introduces complexity to the overall architecture. Since a common AC distribution transformer is not capable of providing DC links, the AC/DC hybrid grid requires a different type of interface. Following the latest technological developments, this interface is the Solid State Transformer (SST) [26] which is an advanced power converter that can provide multiple ports, regardless of the voltage level or type. In this sense, it can be connected to the MV side of the AC distribution line and provide AC and DC connections at both MV and LV levels. This active power converter is modular, scalable

and capable of providing grid-flexible services. Yet, to function properly, it requires advanced control systems [27], which take into account both AC and DC components, have high maintenance requirements and their advantages are reflected in their cost.

Nevertheless, all of these disadvantages can be overcome if particular attention is given to aspects where DC technology may have significant potential, to be firmly established, starting to build from that point forward. The increasing use and development of modern power electronic converters can significantly help for the diffusion of DC technology providing the necessary framework, backed up by the wider application of RES technologies.

Overall, the development of AC/DC hybrid smart microgrids appears to have many advantages, rendering them a key driver in paving the way towards energy efficiency, sustainability and mitigation of anthropogenic climate change. For them to be established in the wider market, the main applications that would highlight their potential need to be taken into consideration.

3. Main applications of AC/DC hybrid smart microgrids

This section aims to showcase modern examples of applications of AC/DC hybrid smart microgrids, which mostly concern buildings, public installations, remote installations, DC-based applications and transportation:

- **Buildings:** One of the most promising applications that would benefit from the AC/DC hybrid smart microgrid architecture is the building sector. Due to environmental as well as economic concerns, PV panels are commonly installed in buildings [28]. Surplus PV generation is usually stored in BESS, which can smooth the mismatch between the PV generation profile and the load profile. Since the PVs and the storage are both installed within the building, they allow the minimization of transmission losses (and thus, the minimization of primary energy consumption and associated CO₂ emissions). Both of these power supply units originally produce DC power. Also, a proportion of the overall load of the building, such as electronic appliances, DC motors, power electronics, batteries, etc., originally consumes DC power [29]. Therefore, it is evident that it would be more beneficial if at least part of the building's power supply was based on DC power distribution, as presented in **Figure 4** [30].

Yet, it should be noted that while this approach could be easily implemented on the side of the DC power supply, it would be more difficult to implement on the DC consumption side, as most DC devices are designed to include (internally) an AC/DC converter to operate with AC grids [31]. This is a barrier that needs to be overcome by the manufacturers of these devices through the proper and widely publicized dissemination of DC capabilities. However, it should be noted that even without the proposed modification of DC loads, it would be beneficial to have a DC sub-grid (in the overall AC grid of the building) for the connections between the PVs, BESS and other DC-based power supply units.

- **District/Distribution level:** The suitability of AC/DC hybrid smart microgrids can be expanded from a single building application to a district-level application, as presented in **Figure 5** [32–34]. As in buildings, so in distribution grids, the penetration of DC-based RES and storage renders the AC/DC hybrid configuration

more effective than the conventional AC one. This topic has gained much attention over the past few years at both Medium Voltage (MV) and Low Voltage (LV) levels.

- **Public installations:** A beneficiary of AC/DC hybrid grids could be various public installations. More specifically, as part of public works and services, older lighting equipment is often replaced by LED technology in most public spaces, roads and highways. Such initiatives help reduce the effect on the environment, as LEDs are more efficient than conventional lighting equipment. Since LED lights constitute DC-based technologies, they would naturally be more efficiently powered by DC lines (incorporated in the overall AC design, thus forming AC/DC hybrid grids) producing a significant economic impact, as public lighting costs are a major part of public expenditure [35, 36].

Figure 4.
Building with AC/DC hybrid smart microgrid architecture.

Figure 5.
District with AC/DC hybrid smart microgrid architecture.

- **Connection of remote/weak installations:** As one of the main advantages of DC lines over their AC counterparts is the capability of power transmission over long distances and the enhancement of power quality and stability, one of the key-applications of AC/DC hybrid grids is the connection to remote installations [37]. These could be small islands or any other case of distant and remote areas, which may be connected to each other or with the robust grid of the mainland through underground or underwater DC cables. Other types of locations could also be remote wind generation parks, built either on islands or offshore [38].
- **DC-based applications:** There is several DC-based applications that could benefit from a direct DC distribution. The two most modern and important are a) data centers and b) EV charging stations.

Data centers are extremely significant facilities, whose importance is gradually increased over time, leading to the increase of required capacity for information storage. Future data centers could entail power levels up to a few MWs in order to properly function. The majority of loads in data centers are of digital nature and operate on DC power. This means that AC connections would not facilitate their development as there would be significant losses and reliability issues due to the required conversion stages. The aforementioned facts favor the adoption of AC/DC hybrid architectures in data centers [39].

Also, as mentioned above, there is a recent, increasing need for efficient EV charging stations. In particular, when it comes to vehicles, the need to a) protect the environment from the emissions of fossil fuels, b) reduce the noise level in the urban field and c) reduce the cost of transportation, has led the car manufacturers to focus on developing and producing EVs. The sales of EVs are gradually increasing around the world and it is estimated that in the near future they shall completely replace fossil-fuel-powered vehicles [40]. EVs need charging at regular intervals and their batteries are inherently DC-power sources [41]. Therefore, charging EVs in DC-based charging stations is more effective than the respective AC alternative, which encourages the research and development towards AC/DC hybrid smart microgrids including EV charging stations [42].

In addition to the arguments described above, it is noted that research is also oriented towards data centers and EV charging stations with PV and/or BESS installations for the purpose of reduction of a) cost, b) energy footprint and c) dependence on the main grid. These amendments furtherly favor the deployment of AC/DC hybrid grids for these applications [43].

- **Transportation:** There is a variety of applications in transport at both MV and LV levels that either already uses DC power or are prompted to do so. Typical examples include ships, urban transport and railways.

Ships constitute a special, isolated from the main grid, application that needs large amounts of power to operate properly. Also, their design has certain limitations, due to constraints imposed by the ship's needs, including constant power availability, space and weight concerns and the presence of pulsed electric loads. DC systems, which have less volume and weight and are more appropriate for handling electronic loads (compared to their AC counterparts) are proposed to be a viable solution for ships, thus forming AC/DC architectures [44].

Urban transport vehicles and railways are one of the early adopters of DC architectures. In many cases, motors and auxiliary circuits inside urban transport vehicles use DC power. As a result, they form DC power systems, drawing power from the main AC grid of the city, through the appropriate AC/DC converters [45].

Overall, there is a variety of applications that could benefit from AC/DC hybrid smart microgrids. **Table 1** summarizes the aforementioned categories of applications, along with some of their main features, i.e., a justification for which type of architecture is suitable for each category, their voltage level and comments. It is noted that the main factors for each application are related either to the increase of RES and DC loads or to the reliability and robustness of DC connections.

Application	Reason for development of AC/DC hybrid architectures	Voltage level	Special comments
Building	Increase of building-integrated RES, BESS storage, and DC load	LV (≤ 400 V)	The use of the building (residence or office) may affect the grid's design (BESS capacity, etc.)
District/Distribution level	Increase of distributed RES and storage units	LV and MV (up to several kV)	A highly DC-based district may also effectively be designed as a DC microgrid
Public installations	Increase of DC load	LV (24 V for LED lighting systems)	LED lighting is a significant part of DC public installations
Connection of remote/weak installations	Robustness provided by DC links and efficiency of power transmission	MV or HV (depending on the application)	Underwater DC cables connect geographical islands
DC-based applications	Increase of DC load (but also possibility for PV-BESS installation)	LV (400 V, etc.)	Data centers, EV charging stations, etc.
Transportation	Reliability, size limitations for the installed components, DC load	LV and MV (usually 750 V, 1 kV, 3 kV, etc.)	Ships, railways, public transport, etc.

Table 1.
Applications of AC/DC hybrid smart microgrids [21, 46, 47].

4. Challenges regarding AC/DC hybrid smart microgrids

Several developments regarding AC/DC hybrid smart microgrids have taken place over the past few years, with fruitful results presented in the worldwide literature. Although, their effectiveness in certain applications is evident and generally accepted by the research community, there is several factors that inhibit their wide deployment, as presented in **Figure 6** [47].

First of all, these developments have been conducted separately, taking into account and focusing on the specific needs of each application, hence lacking a more general and common framework of the application. To establish their place in the market and challenge the dominance of conventional AC grids, a common legislative background for AC/DC hybrid smart microgrid solutions is considered to be a necessity [48]: it is important to establish standards upon which the architecture of AC/DC hybrid smart microgrids can be designed and implemented.

In this sense, DC compatible equipment needs to be developed by the manufacturers [21]. More specifically, one of the main reasons why such advanced grids are researched is the ascending amalgamation of DC devices in the overall load of the system. As mentioned previously, such devices include EVs, computers and other electronic devices, power electronics, DC motors, LED lights, etc. Nevertheless, currently, most of these devices are designed to be powered by AC sources. To be efficiently incorporated in AC/DC hybrid smart microgrids, they need to be designed to be powered by DC sources by incorporating a DC/DC converter [49]. For this purpose, it is imperative to establish mechanisms that promote and provide financial support to the cooperation between public and private entities, researchers and industry, allowing the development of DC-compatible equipment that is not yet available as well as suitable disconnecting and protection devices [50].

Furthermore, there is a generalized requirement for the standardization of the voltage level on hybrid grid applications, new safety regulations and suitable protection mechanisms [51–54]. More specifically, a major challenge for voltage standardization on the DC part of hybrid grids is the use of different voltage levels in distributed generation, residential, commercial and industrial demand sides. So far,

Figure 6.
Challenges for AC/DC hybrid smart microgrids.

the research community has not agreed to use a specific DC voltage level or even set clear limits between what is considered to be “low”, “medium” and “high” voltage, in terms of standardization. Without voltage levels standardization it is impossible to develop appliances, equipment and devices that are directly connected to DC buses. It is inconvenient for manufacturers to design DC products capable of operating with different voltage levels. To speed up the incorporation of DC technologies in the distribution grid, voltage standardization is by far the highest priority. In this way, stakeholders, equipment manufacturers, consumers and users can be attracted to hybrid grids, increasing their readiness level.

5. Conclusions

This chapter reviewed the motives and applications of AC/DC hybrid smart microgrids. This type of grid constitutes a milestone in the evolution of electrical transmission and distribution systems, as it facilitates the efficient incorporation of the majority of RES, storage as well as DC-based loads, while also having AC connections for the service of AC generation and consumption. Indicative applications that would benefit from such architectures include buildings, data centers, EV charging stations, etc. However, the wider adoption of AC/DC hybrid smart microgrids requires a more coordinated effort in terms of the regulatory framework, so that their DC part can be as highly standardized as the AC one.

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Conflict of interest

The authors declare no conflict of interest.

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