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Perspective

DC Microgrids: Benefits, Architectures, Perspectives and Challenges

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Abstract: One of the major paradigm shifts that will be predictably observed in the energy mix is related to distribution networks. Until now, this type of electrical grid was characterized by an AC transmission. However, a new concept is emerging, as the electrical distribution networks characterized by DC transmission are beginning to be considered as a promising solution due to technological advances. In fact, we are now witnessing a proliferation of DC equipment associated with renewable energy sources, storage systems and loads. Thus, such equipment is beginning to be considered in different contexts. In this way, taking into consideration the requirement for the fast integration of this equipment into the existing electrical network, DC networks have started to become important. On the other hand, the importance of the development of these DC networks is not only due to the fact that the amount of DC equipment is becoming huge. When compared with the classical AC transmission systems, the DC networks are considered more efficient and reliable, not having any issues regarding the reactive power and frequency control and synchronization. Although much research work has been conducted, several technical aspects have not yet been defined as standard. This uncertainty is still an obstacle to a faster transition to this type of network. There are also other aspects that still need to be a focus of study and research in order to allow this technology to become a day-to-day solution. Finally, there are also many applications in which this kind of DC microgrid can be used, but they have still not been addressed. Thus, all these aspects are considered important challenges that need to be tackled. In this context, this paper presents an overview of the existing and possible solutions for this type of microgrid, as well as the challenges that need to be faced now.

Keywords: DC microgrids; architectures; hybrid grids; smart grid; unipolar; bipolar

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1. Introduction

In the last few years, a new paradigm emerged regarding electrical distribution networks. Instead of the classical AC networks, which are especially associated with micro- and mini grids, the use of DC networks appeared as a better solution taking into consideration several aspects. One of the aspects is related to the distributed generation (DG) that is associated with renewable energies. Other aspects are the use of energy storage systems, the reliability of electric networks and loads with high-energy efficiency [1,2]. Due to those aspects, DC networks are now considered very attractive, especially in the context of the modern smart power distribution systems.

Due to the several advantages that can be achieved with these microgrids, as well as the referred change in loads and use of storage systems, they can be used in several applications. Examples of these applications are small houses, buildings, data centers and agricultural farms. New realities started to emerge in the last few years, such as charging infrastructures for electric vehicles, which is a good example of a possible application of this kind of microgrid. In fact, electric vehicle fast chargers require a DC power supply, by which proposals for DC microgrids have already started to appear. Prosumers started to play a fundamental role in an electrical distribution Low Voltage (LV) context [3–7]. Their integration is seen as natural in LVDC systems once it will be possible to achieve meaningful savings [8–10]. Another aspect is the impact on social welfare that DC microgrids will bring [11]. This kind of microgrid, especially in the context of off-grid systems, could be an important opportunity to increase the quality of life of many people, particularly those in isolated towns and villages.

Taking into consideration the development of the present technology and the future reality of electrical generators and loads, DC microgrids started to arise as an important alternative to AC infrastructures. It is expected that in the very near future, AC and DC infrastructures will present themselves as complementary solutions [12–16]. In this context, the perspectives for the near future of DC microgrids are presented in this paper.

There are several challenges associated with DC infrastructures that must be overtaken. One important aspect is the definition and standardization of these networks. On the other hand, there are many aspects that must be developed, as is the case, for example, with the appearance of new standards and/or legislation.

Under the several aspects that were referred previously, this paper will present the technology behind the DC microgrids that can be used in several applications in the future. Not many of these applications have already been implemented. In this context, this paper will also present new applications in which this kind of microgrid can successfully be used. Some applications and corresponding solutions are visions of the authors. Finally, we will also focus on the challenges that need to be faced to implement this technology. With all of this in mind, we intend to provide a perspective on the future of these DC microgrids.

Regarding the structure of this paper, it consists of six sections, with the first one being this introduction. In the second section, the typical architectures and configurations that have already been proposed for DC microgrids are presented. In the third section, the benefits that can be obtained through the use of a DC microgrid when compared with traditional AC grids are presented. The possible applications of DC microgrids are described in section four. Some of the possible applications and solutions are visions of the authors. Section five focuses on the challenges ahead that are fundamental for the success of DC microgrids. Finally, in section six, the conclusions of this paper are presented.

2. Architectures and Configurations

One aspect that is not yet standardized is the type of architecture that should be adopted or is the most indicated to a specific application. In reality, there are several possible architectures that can be used to establish a DC microgrid [2,17–23]. These different structures are as follows:

- Single bus topology. This topology is the simplest topology since it is constituted by a single DC bus. Due to that, all generators, storage systems and loads will be connected to the same point (bus). Figure 1 shows two typical examples of this topology, with one being a connection to the electrical grid and the other one being an operation in islanded mode. Besides its simplicity, this topology is also characterized by low maintenance requirements, as well as low costs.
- Radial topology. This topology can be considered as an extension of the single bus. As shown in Figure 2, this topology provides more than one DC bus where each of them are used to connect generators, storage systems and loads. Typically, there are two possible configurations: series and parallel. In the first configuration, two or more DC microgrids can be interconnected in series (Figure 2a), while the other one is interconnected in parallel (Figure 2b). This topology still maintains some simplicity and allows for different voltage levels. Additionally, this topology increases reliability. However, one problem that can appear is some instability during the islanding mode [24–27].

- Ring or loop topology. In this topology, all generators, storage systems and loads will be connected to the same DC bus in a loop way to allow the supply through two sides (Figure 3). Due to this, this kind of topology becomes more reliable when compared with the previous configurations, since in the case of a fault in the DC bus, it is possible to operate in a single bus configuration, and the main problem of this topology is its increased complexity.
- Mesh topology. This topology is characterized by the possibility of including integrate ring (or rings) with radial topologies with a mesh configuration originating in this way (Figure 4). It is characterized by a complex structure that allows for better reliability and flexibility when compared with the previous ones.
- Interconnected topology. The previous topologies were characterized by a single connection to the AC main grid. Thus, in order to improve the reliability of the system, there is also the possibility to connect it to alternative AC grids (two or more), meaning this topology is designated by interconnections. In Figure 5, an example of this kind of topology, in which the DC microgrid is interconnected to two AC grid supplies, is presented.

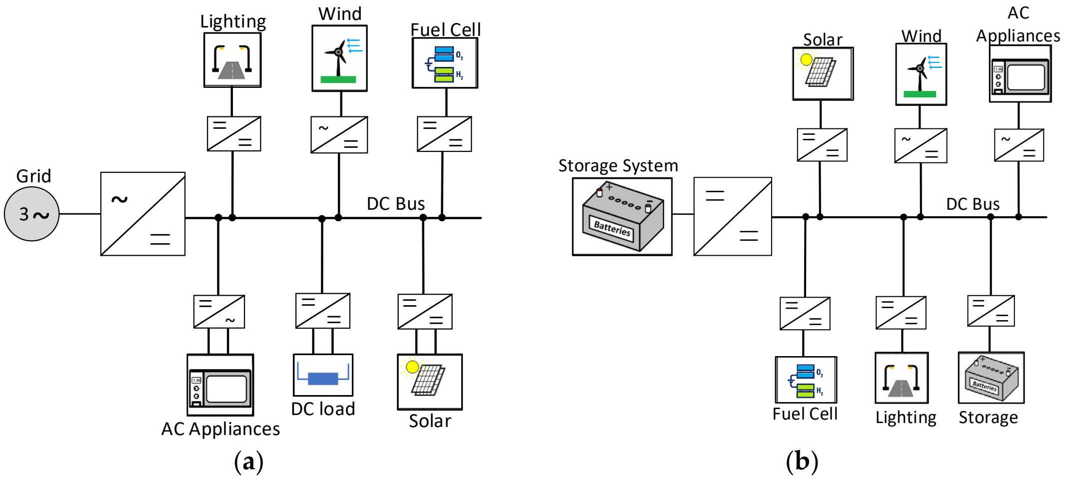


Figure 1. A schematic of typical example of the single bus topology: (**a**) connected to the grid and (**b**) operating in island mode.

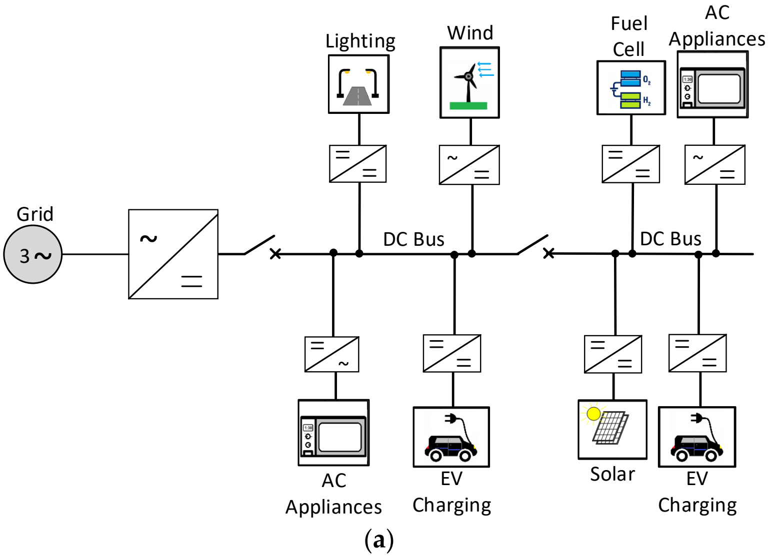
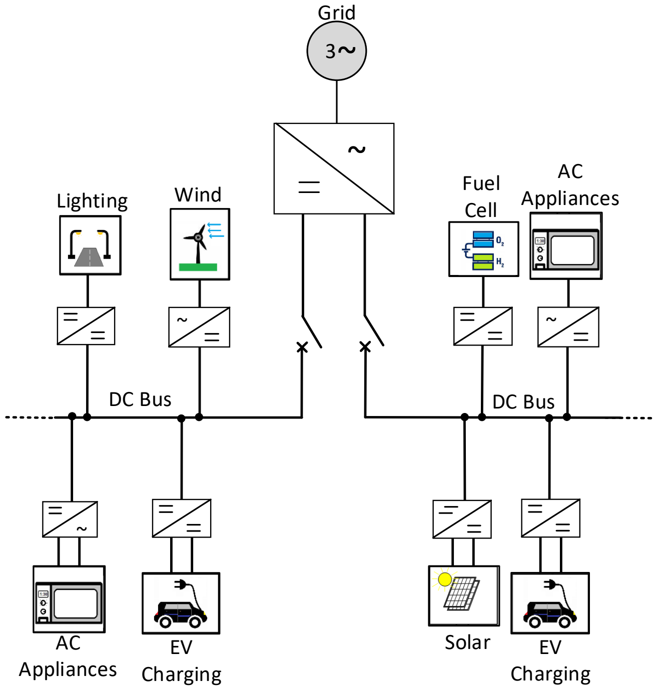


Figure 2. *Cont.*



(**b**)

Figure 2. A schematic of typical example of the radial topology: (**a**) series configuration and (**b**) parallel configuration.

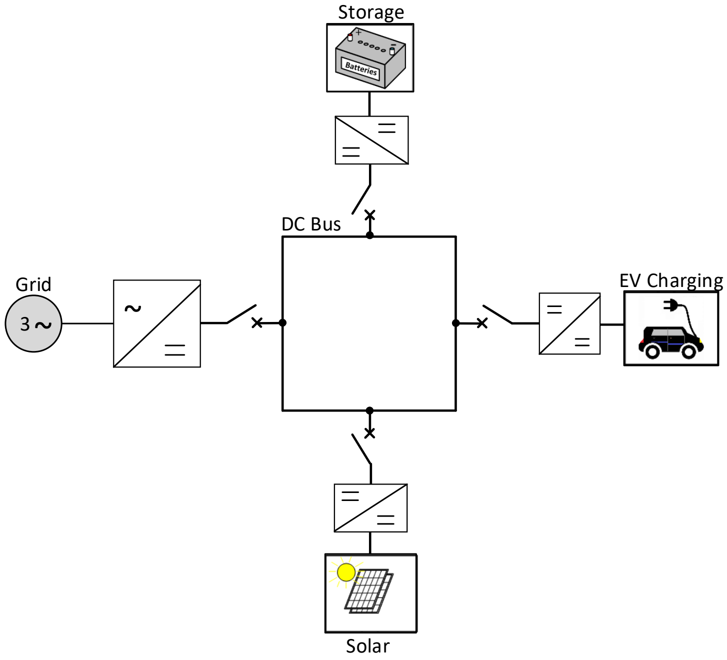


Figure 3. A schematic of typical example of the ring topology.

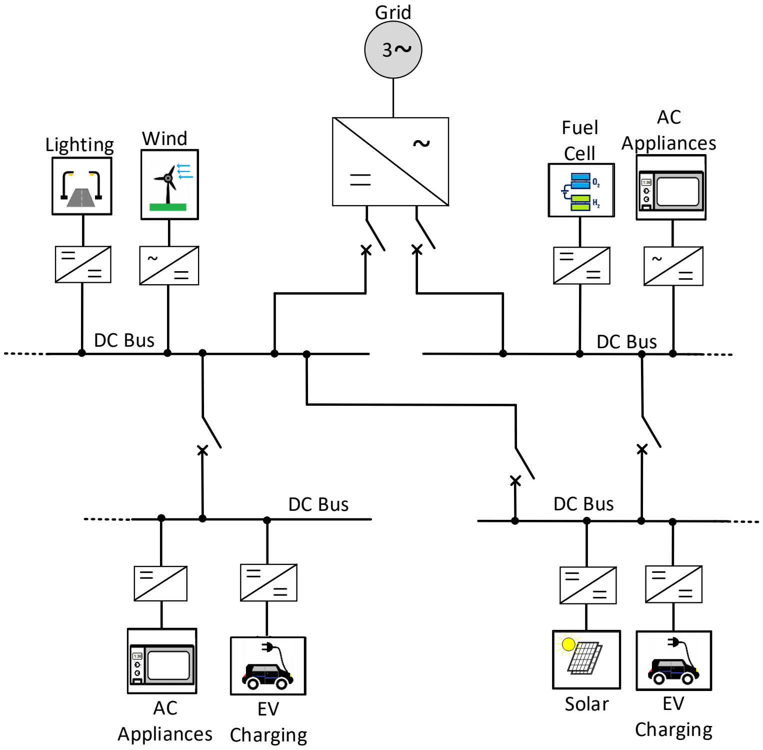


Figure 4. A schematic of typical example of the mesh topology.

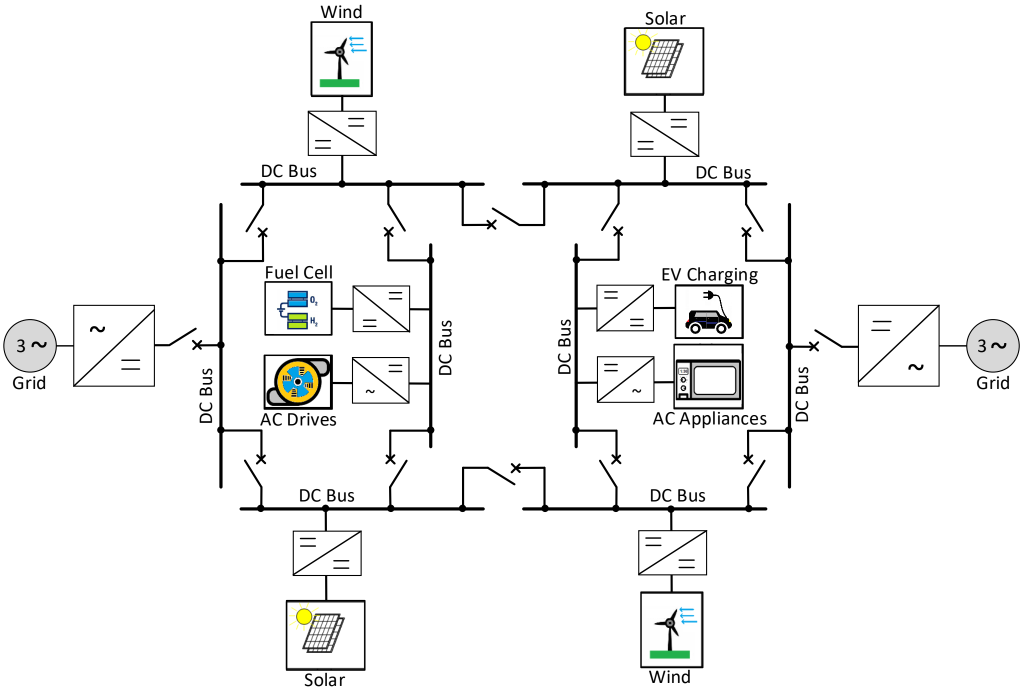


Figure 5. A schematic of typical example of the interconnected topology.

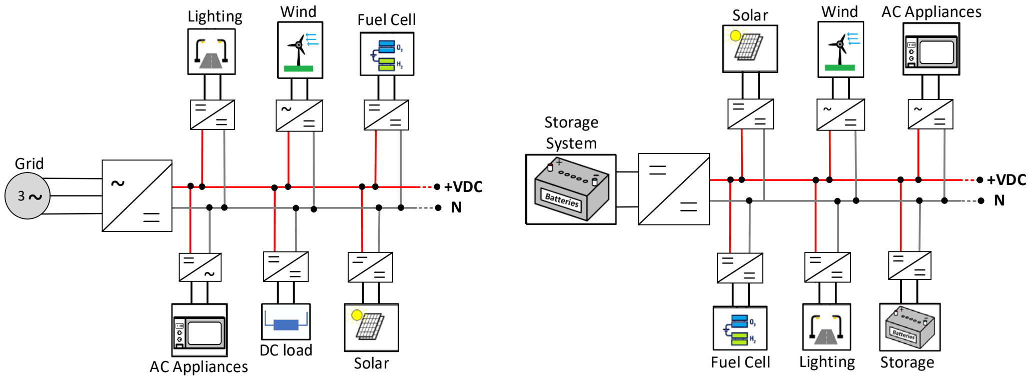
A summary of the DC microgrid topologies and corresponding relevant references associated with each of the structures is presented in Table 1.

Table 1. Summary of the DC microgrid topologies and corresponding references.

DC Structures	References
Single bus topology	[2,17–26,28–30]
Radial topology	[2,17–23,31–35]
Ring or loop	[2,17–23,36–39]
Mesh topology	[2,17–23,31–33,40–42]
Interconnected topology	[2,17–23,43,44]

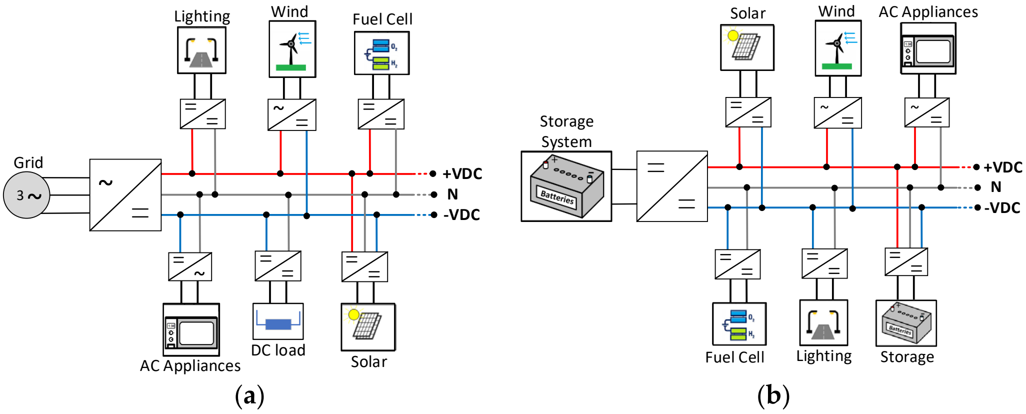
On the other hand, regarding the configurations, the main ones that have been used, tested and studied are the following ones [45–47]:

- Unipolar configuration. This configuration is the simplest one since it is constituted by only two wires. In this configuration, all the generators, loads and storage systems will be connected to the same poles. In Figure 6, two typical examples of this topology are shown, whereby one has a connection to the grid and the other one operates in island mode.
- Bipolar configuration. This configuration is more complex since it is constituted by three wires (a positive pole, neutral pole and negative pole). In this configuration, there are different possibilities to connect the generators, loads and storage system. In fact, they can be connected to different poles (positive and neutral, neutral and positive or to the three poles). It also allows this equipment to be connected to different voltages, namely between the positive and negative pole or one of the poles and the neutral pole. Examples of this type of configuration can be seen in Figure 7, where one has a connection to the grid and the other one is operating in island mode.



(**a**) (**b**)

Figure 6. A schematic of typical example of the unipolar configuration: (**a**) connected to the grid and (**b**) operating in island mode.



(**a**) (**b**)

Figure 7. A schematic of typical example of the bipolar configuration: (**a**) connected to the grid and (**b**) operating in island mode.

A summary of the DC microgrid configurations and the corresponding relevant references associated with each of the structures is presented in Table 2.

Table 2. Summary of the DC microgrid configurations and corresponding references.

DC Structures	References
Unipolar configuration	[45–51]
Bipolar configuration	[45–47,52–59]

Through the comparison of both configurations, the bipolar DC microgrid presented several advantages, such as a higher number of voltage levels (two instead of one), increased efficiency and a power supply with increased quality [17]. Another important feature is related to reliability, which is higher in the bipolar architecture since, in the case of having a fault in one of the wires, the load can be supplied by the other two healthy lines [17–19]. Another positive aspect is that it is possible to reduce the maximum voltage to the ground since it is possible to use the connection between the positive and negative pole to obtain extended voltages. However, there are still some disadvantages associated with the bipolar architecture. The main disadvantage is the requirement of additional wires and the possible appearance of voltage unbalance between the bipolar terminals [46]. This lack of balance can be caused by the use of different loads connected to each of the terminals. Another cause of that unbalance may be the generation. Usually, generators such as PV use a DC/DC converter that will only connect to a single pole, which will contribute in this way to voltage unbalance. However, there are several strategies that can be used to attenuate or eliminate that unbalance [47].

3. Benefits

Classical electrical infrastructures use AC distribution systems. However, in the context of distributed renewable DC generation and storage systems, this type of network is not the most efficient and flexible. Besides that, DC networks have the capability to directly supply most of the electronic loads. Usually, electronic loads require a DC voltage source, by which they typically use a rectifier to allow for their connection to the AC network. However, the addition of these rectifiers reduces the efficiency of the load and increases their cost. In this way, DC infrastructure networks have already been successfully implemented in several specific applications. In accordance with some studies, with the use of these infrastructures, there are efficiency improvements ranging from 12% to 18% [47]. Another aspect in which DC microgrids could be advantageous compared to AC networks is reliability. In fact, as stated before, when adopting the bipolar structure, even in the case of a fault in one of the poles, it is still possible to operate the grid, at least partially. The several advantages associated with this kind of network, compared to AC networks, can be summarized as follows [60–63]:

- The fact that the decentralized generators essentially produce DC power. Thus, the direct connection of these generators to the grid without the need to introduce a new converter (DC/AC) allows for the improvement of the efficiency of the system;
- The importance of storage systems in the context of the decentralized and renewable energy sources. As in the case of the generators, these storage systems (such as batteries) typically also produce and receive DC power, by which their direct integration in the distribution system also allows for the improvement of the efficiency of the global system;
- The fact that the electronic loads are usually supplied by a DC voltage source, by which they can be directly connected to the distribution grid. Most loads require a rectifier in order to provide the required DC voltage source;
- The predicted proliferation of electric vehicles requires a connection to the electrical grids to charge their batteries. Thus, the possibility of directly connecting the electric vehicle to the grid to avoid the rectifier can also improve the efficiency of the global system;
- The reduction in power quality problems that typically affect AC grids. In fact, problems such as voltage sags and swells, flickering, harmonics and imbalances that usually affect AC grids can be avoided in these DC microgrids;
- The lack of requirements about synchronization with the utility grid, as well as reactive power;
- The inexistence of skin effect, by which there will be an entire distribution of the current through the distribution cable. Due to this, there will be a reduction in the losses or the use of smaller section cables;
- The possibility to improve the reliability due to a high capacity to operate in island mode.

Although DC microgrids can provide multiple advantages, there are some drawbacks associated with the change to this kind of infrastructure. One of the main problems is the need for extra costs, which could inhibit the change to this type of technology. Another important factor is the change in mentality, since it is usually not easy to convince people and investors to change. On the other hand, many people can claim that it will be necessary to change from AC loads to DC loads or to include an extra adapter to be used in DC microgrids. However, today, the majority of the loads are electronic loads, meaning that this kind of AC load can be directly used in DC sockets. This will avoid extra costs and will convince people of this change more since they can use their equipment in AC or DC sockets. Typically, AC electronic loads are connected to the socket through a rectifier converter (AC to DC). That converter is usually a single-phase H-bridge diode rectifier (Figure 8a). Taking this into consideration, it is possible to still use the AC equipment since the rectifier allows for operation with a DC input voltage. As shown in Figure 8b, in this case, instead of using the four diodes, only two diodes are used since there is no negative voltage. This is one important factor in the choice of the DC microgrid voltage level for residential applications (and even in other places). For example, the AC voltage requirement for many electronic equipment is 100 to 240 V_{RMS}. Taking this aspect into consideration, the voltage level of the DC microgrid should be higher than that value. On the other hand, in the security context, the use of bipolar DC microgrids can be very interesting since they allow for the reduction in the voltage level of the pole(s), since in this case, voltage levels of ±50 to ±120 V can be used.

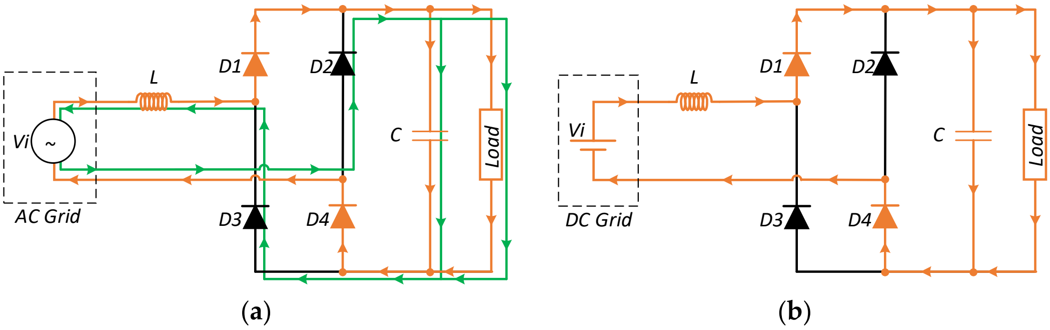


Figure 8. Typical rectifier used in AC electronic loads: (**a**) connection to an AC socket and (**b**) connection to a DC socket.

Another aspect that also must be taken into consideration is the protection of the DC infrastructure, since it is more difficult than the one used in the AC infrastructure. This is an aspect that still needs some research.

A summary of the advantages and the disadvantages of the AC and DC microgrids can be seen in Table 3.

Table 3. Summary of the advantages and disadvantages of AC and DC microgrids.

	AC Microgrid	**DC Microgrid**
Direct integration of the RES (such as PVs) with the need for a DC/AC converter	No	Yes
Direct integration of the ESS with the need for a DC/AC converter	No	Yes
Direct integration of DC loads	No	Yes
Power quality and control of the MGs	Complex	Easy
Need for synchronization	Yes	No
Frequency regulation	Constant, equal to 50 or 60 Hz	No
Skin effect	Yes	No
System protection	Fully developed, not expensive	Underdeveloped, expensive
Standards	Sufficient	Insufficient
Cost of the system	Low	High

4. Perspectives

There are many possibilities to apply DC microgrids, and their implementation could be an important asset over the classical AC grids or microgrids, as stated before. However, until now, only a few applications of DC microgrids have been implemented. Additionally, some of the applications that have already been implemented were part of an experiment or were integrated in a research project. One of the applications of DC microgrids that have already been implicated is associated with data centers, but there are many other applications where DC microgrids can be an important asset.

One application area in which it is predictable that DC microgrids will be adopted is electric vehicles charging systems infrastructures [64–69]. There are some different perspectives on this. One of the perspectives is that the bipolar DC microgrid will be used, as shown in Figure 9 [70,71]. It is possible to see in this figure that this is a case in which a bipolar configuration is very well adapted. Other perspectives, in which the use of a unipolar DC microgrid is adopted, were also proposed [72,73]. One important aspect associated with this microgrid is if the kind of application can easily integrate a storage system. Storage systems in these infrastructures can be very important as they allow for the attenuation of load peaks that could appear. It is also possible to easily integrate renewable energy sources such as PV generators.

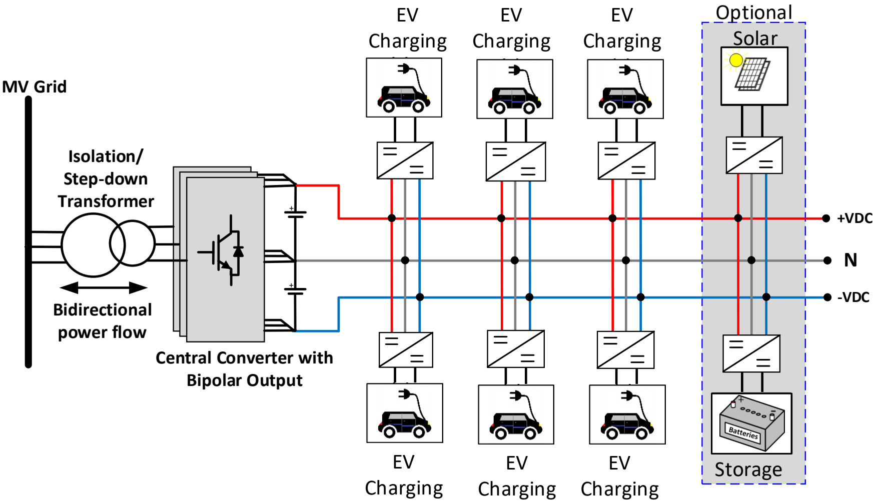


Figure 9. One of the perspectives for a DC microgrid to be used in electric vehicles charging systems infrastructures.

Another possible implementation is the interconnection of a Medium-Voltage DC grid with a Low-Voltage DC grid. This will be very interesting in areas that are near residential consumers where there are some renewable energy generation parks with some dimension to be connected to a Medium-Voltage DC grid. Figure 10 presents a possible scheme of this kind of infrastructure. As shown by this figure, since residential consumers are connected to an LV grid, a transformer is required. However, this is a particular case in which using solid state transformers (SST) is extremely desirable. Another aspect is regarding the LV grid configuration, which in this case can also be an asset.

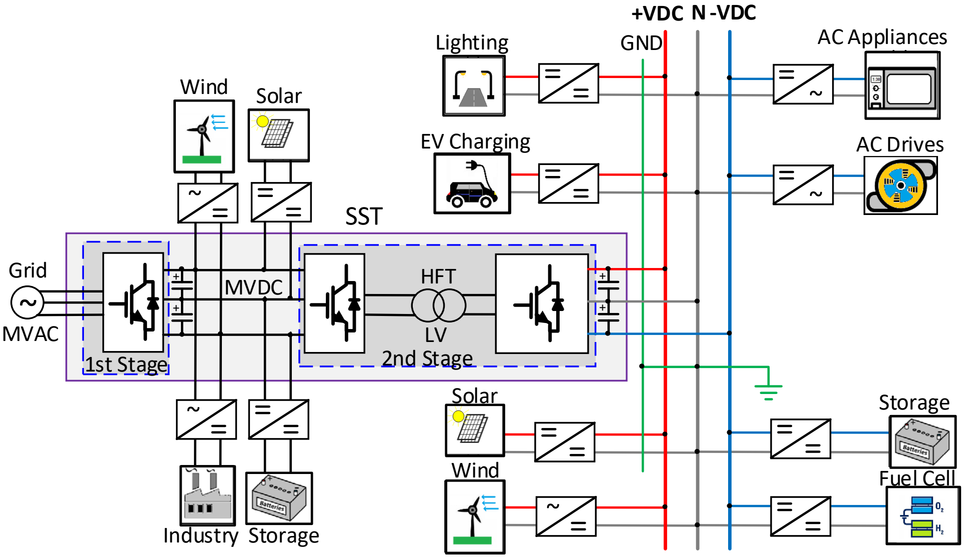
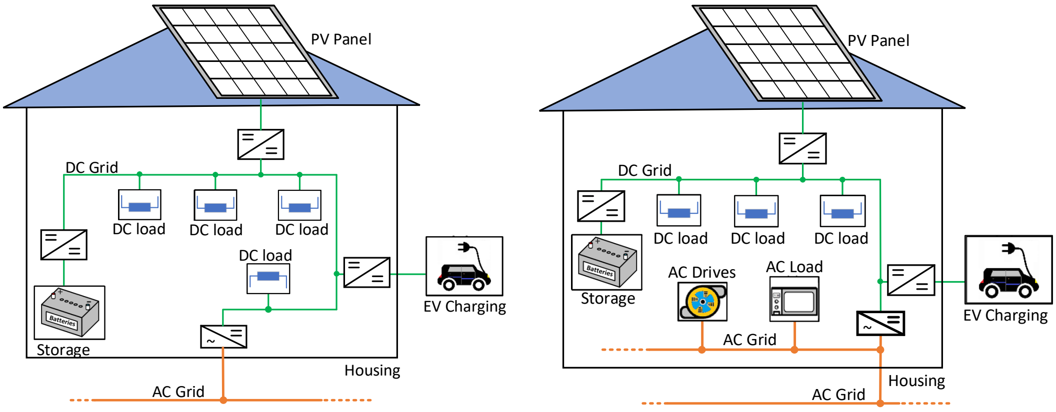


Figure 10. A vision for a DC infrastructure in which an interconnection of a Medium-Voltage DC grid with a Low-Voltage DC grid is used.

Another application area in which DC microgrids can play an important role in the future is residential areas and buildings [74–82]. DC microgrids can especially be used in residential individual houses, as nowadays, many of them already have photovoltaic generators. This has been a case of success regarding the use of renewable energies associated with consumers (typically designated as prosumers). However, one aspect that has been verified is that at peak hours, many of the prosumers do not harness the produced energy. Some of the prosumers sell the energy, but typically the price is not the best one. In this way, for the future, the use of storage systems is expected. This can be explored in the context of second live batteries, which are predicted to be available in the context of the massive use of electric vehicles. Thus, a possible structure for individual residential houses is the one presented in Figure 11. A parallel structure in which there is an AC network and a DC network could be the possible best solution, since it will at least allow the AC networks to be supplied without the need to add an extra power electronic converter (DC to AC).



(**a**) (**b**)

Figure 11. Possible structure of the electrical infrastructure for individual residential level: (**a**) only a DC network and (**b**) parallel infrastructure of AC and DC networks.

Another aspect that is similar to the one presented for the individual residential houses is buildings (residential or offices). In this case, the same parallel infrastructure can be considered as one of the most desirable. One perspective for one simplified scheme only considers DC infrastructure connecting to the renewable energy generators, storage systems and eventually the electric vehicles charging system, as shown in Figure 12a. In this scheme, there is only one interconnection between the DC infrastructure and the AC infrastructure. However, the reliability and efficiency of the electrical distribution system can be improved if several interconnection points are used instead of only one interconnection. Furthermore, the reliability of the system also allows for the optimization of the power flow and increases the capacity to provide ancillary services to the AC network. A possible scheme of this system can be seen in Figure 12b. Another perspective considers a DC infrastructure inside the residences (only DC or parallel DC and AC). Again, the infrastructure can be constituted by one or several interconnections in the main DC infrastructure that will supply each residence, as shown in Figure 13. At least for the main DC infrastructure that will supply each residence, the bipolar configuration is the most indicated.

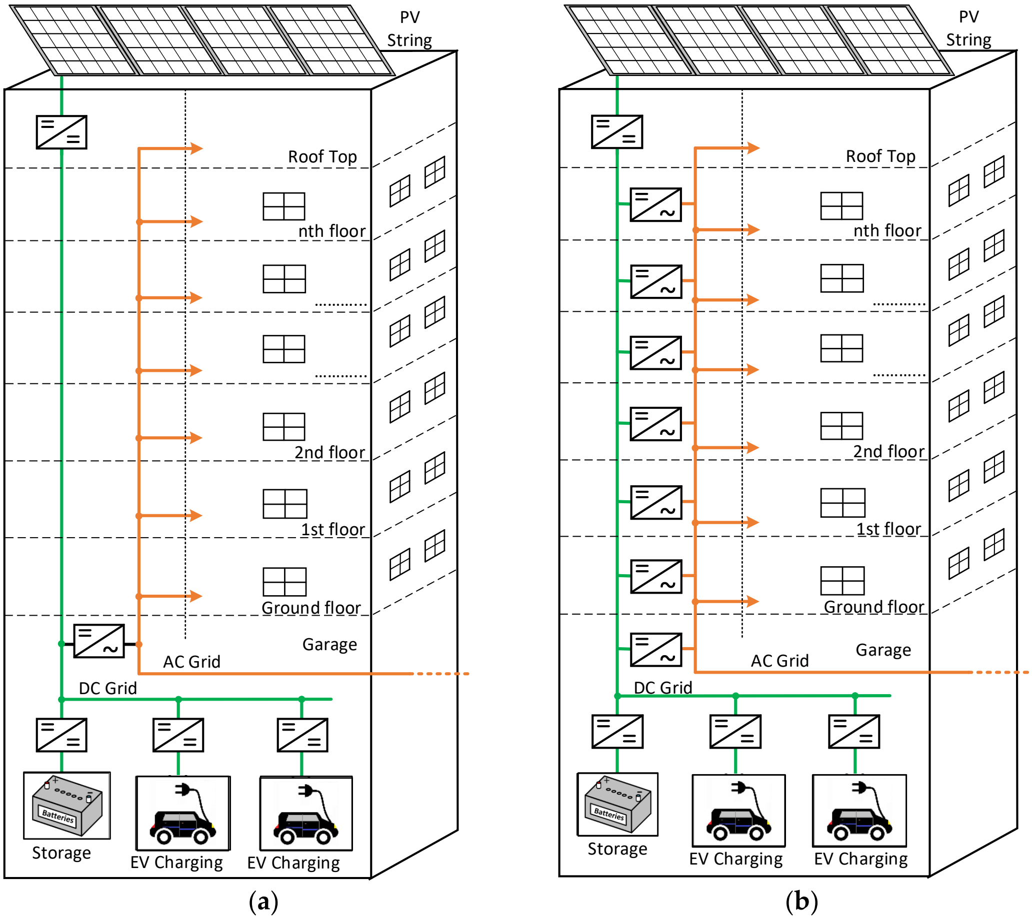
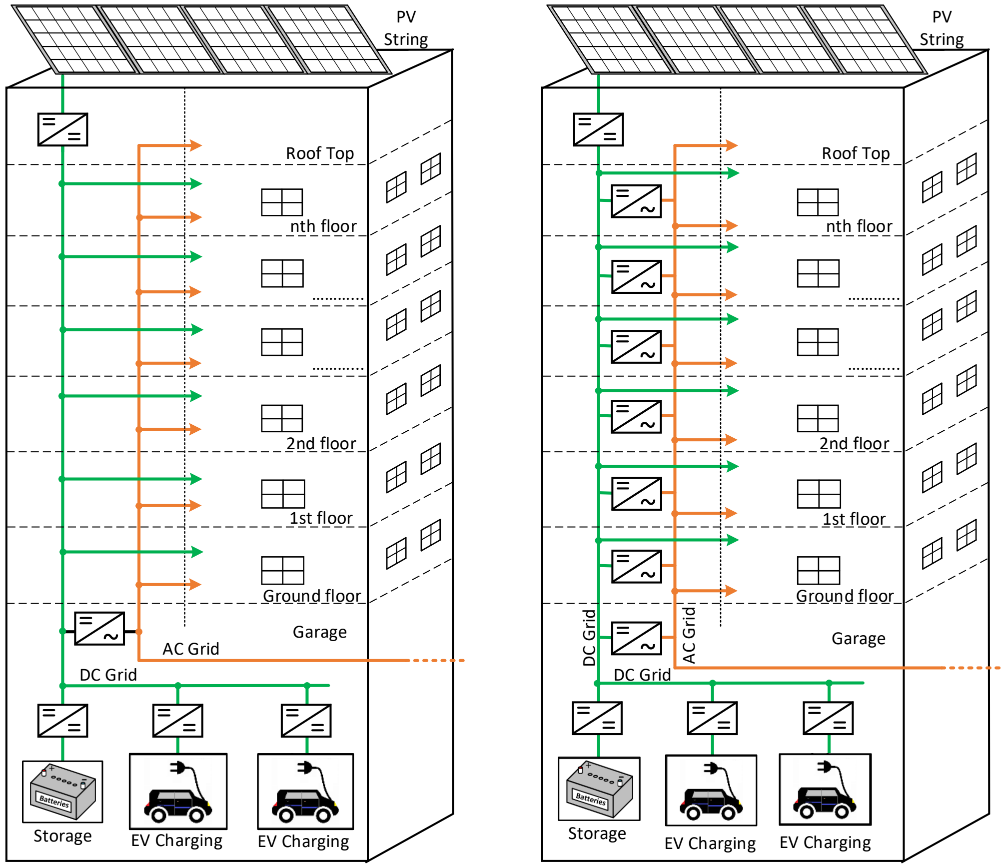


Figure 12. Possible structure of the electrical infrastructure of buildings in which only a DC infrastructure connects to the renewable energy generators, storage systems and the electric vehicles charging system: (**a**) only with one interconnection and (**b**) with more than one interconnection.

Another area in which a parallel infrastructure can be very important in the near future is LV electrical networks. Since it is predicted that practically all homes and buildings will include renewable energy sources and eventually energy storage systems, this parallel structure makes sense. This can be very important in the context of renewable energy communities [9,83,84]. One perspective for this parallel infrastructure can be seen in Figure 14. This infrastructure will allow for improvement in the efficiency and reliability of the system.

It is also expected that DC microgrids will play an important role in rural areas [32,85–88]. This is highly recommended especially in the context of an isolated DC infrastructure due to the fact that there are not any AC infrastructures nearby. In this case, the DC microgrid can be constituted by renewable energy sources (for example, photovoltaic generators), fuel cells, storage systems, pumping systems, warehouses and support houses. In Figure 15 a typical installation that can be used in this kind of rural application is presented.



(**a**) (**b**)

Figure 13. Possible structure of the electrical infrastructure for buildings in which it is also considered a DC infrastructure inside the residences: (**a**) only with one interconnection and (**b**) with more than one interconnection.

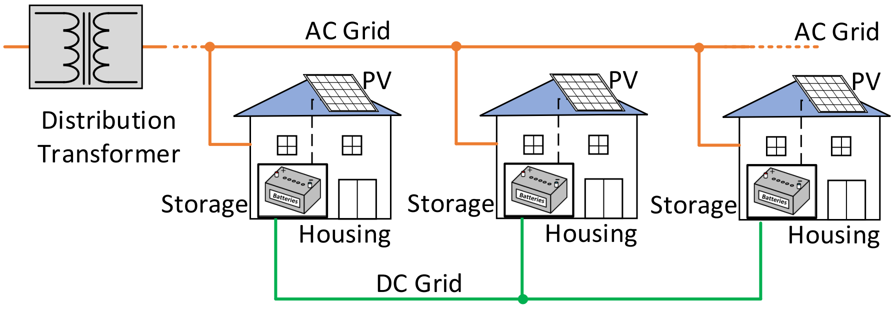


Figure 14. A perspective on parallel AC and DC infrastructure in LV electrical networks.

There are also other interesting applications in which DC microgrids can play an important role. The applications have already been implemented or referred to by other authors [88–91]. Applications related to the transportation sector is one of those areas. One of the areas in which an important boost is expected is related to ships [92–94]. The use of these DC microgrids associated with the supply of the trains is another perspective [95–98]. Data centers are installations in which DC microgrids have already been used with success [99,100]. Due to this success, it is expected that in the future, more and more data centers will be supplied by DC microgrids.

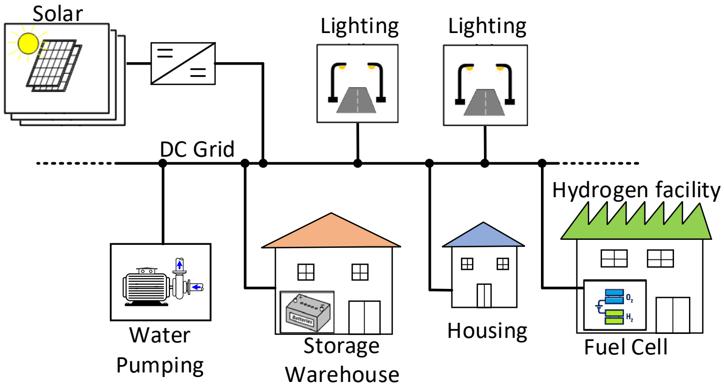


Figure 15. A vision for an isolated DC infrastructure in a rural context.

A summary of the possible applications of DC microgrids and the corresponding relevant references associated with each of the applications is presented in Table 4.

Table 4. Summary of the possible applications of DC microgrids and corresponding references.

Possible Applications	References
Electric vehicles charging systems infrastructures	[64–73]
DC infrastructure in which an interconnection between a Medium-Voltage DC grid and a Low-Voltage DC grid is used	Vision of the authors
Electrical infrastructure for individual residential level	[74–79]
Electrical infrastructure for buildings	[80–82], Vision of the authors
Parallel AC and DC infrastructure at level of LV electrical networks	Vision of the authors
Isolated DC infrastructure in a rural context	[32,85–88]
Ships	[89–94]
Trains	[95–98]
Data Centers	[99,100]

Some insights about what the future of DC electrical distribution infrastructures can be is presented in this paper. The accomplishment of these approaches can change the actual electrical distribution system in a huge way. For practically all of these ideas, the extinction of the AC electrical distribution system was not considered; rather, their coexistence was considered.

5. Challenges

One of the most important aspects that is fundamental for the development of DC microgrids is related to the standards. For example, one particular aspect that is critical is the definition and standardization of the voltage levels associated with the different DC microgrids. Some studies have already been conducted regarding the best voltage levels to be used [19], but they are still not defined by law. The developed DC microgrids use different voltage levels. Another aspect that is fundamental and still needs some new standards and legislation is the security of people and installations [37,101,102].

The subject of the isolated DC microgrid is something that has been studied in the last few years. However, this is still considered a challenge since there are many aspects that need to be addressed, such as, for example, the inertial control associated with these networks [103–106]. The voltage of DC microgrids is prone to oscillation. Several factors are responsible for this, such as DC converters presenting negative damping performance, the interaction between the DC microgrid and the DC converters and the DC voltage control loop with positive feedback [107–111].

Another aspect that needs to be better addressed is the control of isolated DC microgrids without the incorporation of storage systems [112]. These kinds of solutions can be implemented in rural and deprived regions, avoiding storage systems and, consequently, allowing for low-cost solutions to be obtained. In fact, there are regions where during the day, the use of PV generators could produce enough energy for remote applications. This is the case with water pumping and small loads, which can be connected to small houses or warehouses. This solution can also be used to replace electrical installations that are supplied by diesel or biofuel generators. This kind of backup power supplies can be a solution for small-scale microgrids since it presents some advantages, such as reducing investment costs, easily being moved and even being considered green if using biofuels. However, if a storage system is not used, some problems may arise due to the fact that these generators present a low response speed and need some time to reach the required and stable power. In this way, it is fundamental to perform studies about the stability and inertia of the grid, considering only renewable generators such as the PV. Another aspect that has been studied in the last few years is the control and stability of DC microgrids [113,114]. This is an area that still requires much research. Like the classical AC grids, DC microgrids are also affected by problems of faults and instabilities, which will cause challenges that are associated with their protection system. These challenges are associated with several aspects. This kind of microgrid faces several problems caused by different aspects such as load variations, the existence of maximum power point tracking (MPPT) controls in DERs, input power fluctuations, the appearance of faults, etc. [17,115–117]. Another important aspect is that contrary to what happens in AC microgrids, DC microgrids do not have the natural current zero crossing, by which the extinction of the arc in the protection system open contacts is much more complex [118,119]. In addition to that, there is a lack of dedicated standards, which makes this topic even more complex. Taking all these aspects into consideration and the little work that has been conducted in this area, there is still a need for a lot of research.

6. Conclusions

DC microgrids can be seen as a game changer in the near future regarding electrical distribution networks. A paradigm in which AC distribution networks will coexist with DC distribution networks is what is expected in the predicted future. This change will probably be boosted due to the change from centralized production to a renewable decentralized generation, and also because of the importance that storage systems will play in this new context. In addition, the change in classical loads to DC loads is also another aspect that will contribute to this change. Aspects related to the adaptation of AC loads to DC microgrids were focused on. It was verified that typical AC loads can be directly used in DC microgrids, avoiding adapters and changes in the equipment. This also brings important cost savings for this transition. Under this context, the possible DC microgrid voltage level to allow the direct use of this equipment was also analyzed. However, to achieve this purpose, much research, developments, studies and experiences are still needed. One of the aspects that was focused on in this paper was the technology behind the DC microgrids that can be used in several applications in the future. Not many applications have already been implemented. Thus, in this context, this paper also presented some perspectives about possible solutions and applications for the DC microgrids. Some of them were perspectives of the authors that could be possible solutions in the near future. However, it was also mentioned that in addition to the importance of research and developments, there are also some other important aspects that must be addressed. That is the case with the definition and development of new standards and new legislation for these networks. All these aspects were addressed with the goal of providing a perspective on the future of DC microgrids.

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