AC and DC tecnology in microgrids: a review

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Abstract

Microgrids are a suitable, reliable and clean solution to integrate distributed generation into the mains grid. Microgrids can present both AC and DC distribution lines. The type of distribution conditions the performance of distribution line and implies different features, advantages and disadvantages in each case. This article analyses, in detail, all this parameters for AC and DC microgrids in order to identify and describe the available alternatives for building and configuring a microgrid. Elements and issues involved in the implementation and development, such as protections, power converters, economic analysis, availability, etc. are discussed and described. This analysis constitutes a tool for selecting a suitable configuration of a microgrid adapted to the needs in each situation. In addition, the article provides a picture of the current situation of microgrids, and identifies and proposes future research lines.

Keywords: Distributed generation, Microgrids, AC technology, DC technology

1. Introduction

The penetration of distributed generation on the mains grid has increased greatly during the last years due to its several advantages. It is mainly based on renewable resources which reduces the environmental impact, and allows to exploit and harvest local energy sources. This growing presence of distributed generation requires an analysis of its impact on the mains grid in order to minimize losses, line loadings, and reactive power requirements [1]. On the other hand, it is a challenge to integrate renewable energy sources directly into the mains grid because of their intermittence, randomness and the uncertainty caused by meteorological factors. In this sense, as microgrids integrate distributed and renewable sources, energy storage devices and large variety of loads, they are a suitable interface between this distributed generation and the mains grid [2, 3].

The microgrids definition states that; they are local distribution systems that include generation, storage and load capabilities, and they can work isolated or connected to the mains grid [4]. This ability for operation both connected and disconnected from the mains grid improves the reliability and power quality of the users connected to them. In addition, if these microgrids are planned following an ecodesign, nearly-zero energy buildings (NZEB) can be obtained [5].

Microgrids can be designed to support alternating current (AC) or direct current (DC). Each alternative has distinctive features, which imply different advantages and disadvantages that need to be pondered. Comparatives between the two type of microgrids in terms of control, protections and power losses are provided in [6–9]. Following the same line, the present article presents a detailed study of AC and DC microgrids that provides the main characteristics of the components of each type of microgrid. The work also discusses and analyses technical, economic and regulation issues such as available power converters architectures, applicable directive, monitoring systems, economic analysis, etc. The main objectives of this analysis are:

- Highlighting the advantages and drawbacks of each technology.
- Identifying and classifying feasible configurations and architectures require to implement a microgrid.

The aforementioned objectives become a tool that allows to choose the most suitable microgrid that fulfils the specifications required in a given situation. In addition, these analysis constitutes a picture of the microgrids state of art, and proposes the research lines to deal with microgrids current needs, and to further develop them.

2. Description of a microgrid

Microgrids are integrated systems in which distributed energy resources (DERs) create a grid that feeds a variable number of distributed loads. Both elements constitute the main body of a microgrid.

DERs, can be classified into two groups (Fig. 2):

- *Distributed generators (DG)*. Electric microgrids include different types of DGs that can be based on either renewable or non-renewable resources. This characteristic allows to adequately exploit the available resources in each location (wind, sun, biomass, etc.) (Fig. 2). Tables 1 and 2 summarize the main types of distributed generators [1, 10–12]. This table highlights that non-renewable based technologies provide yet higher efficiencies. It also shows that wind and small hydro-power based systems offer the highest efficiencies among the renewable based technologies. Ocean energy, although is a very promising source of energy, still requires further research and development to become profitable and reach the market with guarantees of success [10].
- *Storage systems (SS)*. The use of SSs improves the stability, power quality, reliability of supply and the overall performance of a microgrid [13, 14]. Table 3 summarizes some key energy storage technologies available for microgrid applications [15–17]. It is interesting to underline that, even if superconducting magnetic energy storage (SMES) provides high efficiency, this technology is still in the demonstration stage. Table 3 also shows that there are other technologies such as pumped hydro storage (PHS) or compressed air energy storage (CAES) that, in spite of their lower efficiencies, have higher capacities with longer lifetimes. There are different procedures to estimate the amount of power that a SS requires. Parameters and considerations for sizing the energy storage in stand alone systems can be found in [18]. In addition, [19] provides models for the same purpose, that also guarantee safe energy supply and help to reach suitable power quality in the microgrid. For the particular case of lead-acid batteries in stand-alone photovoltaic systems, some guidelines and recommended practices for its sizing can also be found in [20].

There is a wide range of loads (residential, industrial, etc.) (Fig. 2) that can be connected to a microgrid. Two main groups are considered, critical/sensitive and Non critical loads [21]. This classification is often performed by the microgrid central controller (MGCC) [22], but can also be done in a decentralised manner by agents [23], both alternatives are detailed on section 9.

Besides the aforementioned elements, microgrids require other infrastructures (Fig. 2):

Table 1: Main technologies of non-renewable DGs.

Energy based technology type	**Primary energy**	**Output type**	**Module power (kW)**	**Electrical efficiency (%)**	**Overall efficiency (%)**	**Advantages**	**Disadvantages**
Reciprocating engines	Diesel or gas	AC	3-6000	30-43	~ 80-85	✓Low cost ✓High efficiency ✓Avility to use various inputs	✗Environmentally unfriendly emissions
Gas turbine	Diesel or gas	AC	0.5-30000	21-40	~ 80-90	✓High efficiencies when using with CHP ✓Environmentally friendly ✓Cost effective	✗Too big for small consumers
Micro-turbine	Bio-gas, propane or natural gas	AC	30-1000	14-30	~ 80-85	✓Small size and light weight ✓Easy start-up and shutdown ✓Low maintenance costs	✗Expensive technology ✗Cost-effectiveness sensitive to the price of fuel ✗Environmentally unfriendly emissions
Fuel cell	Ethenol, H_2, N_2, natural gas, PEM, phosphoric acid or propane	DC	1-20000	05-55	~ 80-90	✓One of the most environmentally friendly generator ✓Extremely quiet ✓Useful for combined heat and electricity applications	✗Extracting hydrogen is expensive ✗Expensive infrastructure for hydrogen

Table 2: Main technologies of renewable DGs.

Energy based technology type	**Primary energy**	**Output type**	**Module power (kW)**	**Electrical efficiency (%)**	**Overall efficiency (%)**	**Advantages**	textbfDisadvantages
Wind	Wind	AC	0.2-3000	–[(1)]	~ 50-80	✓Day and night power generation ✓One of the most developed renewable energy technology	✗Still expensive ✗Storage mechanisms required
Photovoltaic systems	Sun	DC	0.02-1000	–[(1)]	~ 40-45	✓Emission free ✓Useful in a variety of applications	✗Storage mechanisms required ✗High up-front cost
Biomass gasification	Biomass	AC	100-20000	15-25	~ 60-75	✓Minimal environmental impact ✓Available throughout the world ✓Alcohols and other fuels produced by biomass are efficient, viable, and relatively clean burning	✗Still expensive ✗A net loss of energy in small scale
Small hydro power	Water	AC	5-100000	–[(1)]	~ 90-98	✓Economic and environmentally friendly ✓Relatively low up-front investment costs and maintenance ✓Useful for providing peak power and spinning reserves	✗Suitable site characteristics required ✗Difficult energy expansion ✗Environmental impact
Geothermal	Hot water	AC	5000-100000	10-32	~ 35-50	✓Extremely environmentally friendly ✓Low running costs	✗Non-availability of geothermal spots in the land of interest
Ocean energy	Ocean wave	AC	10-1000	–[(1)]	–[(1)]	✓High power density ✓More predictable than solar or wind	✗Lack of commercial projects ✗Unknown operations and maintenance costs
Solar thermal	Sun and water	AC	1000-80000	30-40	~ 50-75	✓Simple, low maintenance ✓Operating costs nearly zero ✓Mature technology	✗Unknown operations and maintenance costs ✗Low energy density ✗Limited scalability

[1]No data available.

Table 3: Main technologies of SSs.

Technology	**Efficiency (%)**	**Capacity (MW)**	**Energy density (Wh/kg)**	**Capital (€/kW)**	**Lifetime (years)**	**Maturity**	**Environmental impact**	**Examples**
TES(2)	30-60	0-300	80-250	140-220	5-40	Developed	Small	Solar two Central Receiver Solar Power Plant, California (USA)
PHS(3)	75-85	100-5.000	0.5-1.5	400-1500	40-60	Mature	Negative	Rocky River PHS plant, Hartford (USA)
CAES(4)	50-89	3-400	30-60	250-1500	20-60	Developed	Negative	Huntorf (Germany) and McIntosh, Alabama (USA)
Flywheel	93-95	0-25	10-30	250	~15	Demonstration	Almost	Commercially supplied by AFS-Trinity (USA), Beacon Power (USA), Piller (USA), etc.
Pbacid battery(5)	70-90	0-40	30-50	200	5-15	Mature	Negative	BEWAG Plant, Berlin (Germany)
NiCd battery(6)	60-65	0-40	50-75	350-1.100	10-20	Commercial	Negative	Golden Valley, Alaska,(USA)
NaS battery(7)	80-90	0.05-8	150-240	700-2.100	10-15	Commercial	Negative	Tokyo Electric Power Company (Japan)
Li-ion battery(8)	85-90	0-1	75-200	3.000	5-15	Demonstration	Negative	Kyushu Electric Power and Mitsubishi Heavy Industries (Japan)
Fuel cells	20-50	0-50	800-10.000	350-1.100	5-15	Developing	Small	Topsoe Fuel Cell, Lyngby (Denmark)
Flow battery	75-85	0.3-15	10-50	400-1.100	5-15	Developing	Negative	Innogys Little Barford Power Station (UK)
Capacitors	60-65	0-0.05	0.05-5	250	~5	Developed	Small	Commercially supplied by SAFT (France), NESS (Korea), ESMA (Russia) etc.
Supercapacitors	90-95	0-0.3	2.5-15	200	>20	Developed	Small	PowerCache (Maxwell, USA), ELIT (Russia), PowerSystem Co. (Japan), Chubu Electric Power (Japan), etc.
SMES(9)	95-98	0.1-10	0.5-5	200	>20	Demonstration	Positive	Wisconsin Public Service Corporation (USA)

[2]TES: Thermal Energy Storage.
[3]PHS: Pumped Hydro Storage.
[4]CAES: Compressed Air Energy Storage.
[5]Pb-acid battery: Lead-acid battery.
[6]Ni-Cd battery: Nickel-Cadmium battery.
[7]Na-S battery: Sodium-sulfur battery.
[8]Li-ion battery: Lithium-ion battery.
[9]SMES: Superconducting Magnetic Energy Storage.

- *Point of common coupling (PCC)* (Fig. 2 - 2). Microgrids can operate connected or disconnected from the mains grid. PCC constitutes the gateway between both grids. This connection can be performed through switchgears and power converters, which are detailed on section 4.

- *Distribution* (Fig. 2 - 3). The main elements of a microgrid (DERs and loads) are interconnected with distribution lines. Meanwhile AC microgrids use single phase or three phase lines, the distribution in DC microgrids is monopolar, homopolar or bipolar (section 5).

- *Protections* (Fig. 2 - 4). Microgrids, either connected or disconnected to the mains grid, must have protection mechanisms that guarantees safe operation. These protection elements must be designed following different principles and parameters. Besides, they must allow to be configured in different manners (section 6).

- *Monitoring* (Fig. 2 - 5). There are many parameters in a microgrid such as voltage, frequency, power quality, etc., that must be continuously supervised by means of a monitoring system. Its main components and features for AC and DC microgrids are described in section 7.

- *Power converters* (Fig. 2 - 6). DERs and loads are generally connected to the distribution lines of the microgrid through power converters. They adapt the currents and voltages levels of the microgrid to the connected units. According to the type of microgrid, different type of power converters are used (section 8).

- *Control* (Fig. 2 - 7). In a microgrid, there are different sources and mechanisms available to gather information. This information requires further processing, which eventually implies that certain tasks need to be performed and coordinated, such as load sharing, voltage level control, electric generation, etc. Both AC and DC microgrid have a hierarchical control system that carries out such tasks. Section 9 explains in detail this control system.

Finally, deployment and maintenance of microgrids must ponder the next practical issues (Fig. 2):

- *Regulatory issues* (Fig. 2 - 8). Microgrids need a regulatory framework in order to provide a successful development and implementation. Standardization of AC and DC microgrids has progressed during the last years because there are currently under development several projects that deal with this objective (section 10).

- *Economic analysis* (Fig. 2 - 9). An analysis of the cost and benefits of a microgrid requires to consider multiple factors and variables. Section 11 describes which are those parameters and methodologies to perform economic analysis of microgrids.

The aforementioned elements and issues mainly depend on the technology (AC or DC) of the distribution line of the microgrid. At the same time, because microgrids can be connected to AC and DC transmission systems (Fig. 2 - 1) with different advantages and disadvantages (section 3). The next sections deal with all these questions and identify the characteristics and features of the transmission systems according to the type of technology used.

Table 4: Principle HVDC installations.

Continent	Location	Fig. 2	HVDC links
Africa	DR Congo	1	Inga-Shaba
	Mozambique-S. Africa	2	Cahora Bassa
America	Brazil	3	Itaipu I and II
		4	Rio Madeira
	Canada	5	Vancouver I and II
		6	Nelson River I, II and bipole II
		7	Eel River
		8	Chateauguay
		9	Madawaska
		10	McNeill
		11	Nicolet Tap
	Canada-USA	12	Des Cantons-Comerford
		13	Quebec-New England
	Paraguay	14	Acaray
	U.S.A	15	Pacific Intertie and Pacific Intertie upgrade
		16	Square Butte
		17	David A. Hamil
		18	CU project
		19	Eddy County
		20	Oklaunion
		21	Blackwater
		22	Highgate
		23	Miles city
		24	Intermountain power project
		25	Sidney (Virginia Smith)
		26	WelchMonticello
		27	Rapid City DC tie
		28	Lamar
Asia	China	29	TSQ-Beijao
		30	Three Gorges-Changzhou
		31	Three Gorges-Quangdong
		32	Guizhou-Guangdong
		33	Three Gorges-Shanghai
		34	Jinping-Sunan

Continent	Location	Figs. 2 and 3	HVDC links
Asia	India	35	Vindhyachal
		36	Sileru-Barsoor
		37	Rihand-Delhi
		38	Chandrapur-Ramagundum
		39	Chandrapur-Padghe
		40	Gazuwaka-Jeypore
		41	East-South Intercon.
		42	Vizag I and II
	Japan	43	Sakuma
		44	Shin-Shinano
		45	Hokkaido Honshu
	Philippines	46	Leyte-Luzun
	South Korea	47	Haenam-Cheju
	Thailand-Malaysia	48	Thailand-Malaysia
Europe	Austria	49	Duernrohr
		50	Vienna-South east
	Denmark-Germany	51	Kontek Interconnection
	Denmark-Sweden	52	Konti-Skan I and II
	Estonia-Finland	53	Estlink
	Finland-Sweden	54	Fenno-Skan
	France-United Kingdom	55	Les Mandarins-Sellindge
	Greece-Italy	56	Galatina-Arachthos
	Ireland-Scotland	57	Moyle
	Italy	58	Sardinia
		59	Sacoi
	Norway	60	Valhall offshore
	Norway-Denmark	61	Skagerrak I, II and III
	Norway-Netherlands	62	NorNed
	Russia	63	Volgograd-Donbass
		64	Vyborg
	Sweden	65	Gotland I, II and III
	Sweden-Germany	66	Baltic Cable Project
	United Kingdom	67	Kingsnorth
Oceania	Australia	68	Broken Hill
	Australia-Tasmania	69	Basslink
	New Zealand	70	Inter-island

3. Transmission system

The main characteristic of microgrids is that they can work both connected or disconnected from the mains grid (Fig. 2 - 1). Nowadays, the majority of power transmission lines use three phase AC technology [24] (Fig. 2 - 1, 1a). However, in recent years, DC high voltage direct current (HVDC) technology (Fig. 2 - 1, 1b) has become more popular for power transmission due to the advantages that offers, such as high power density, controlled emergency support, no contribution to short circuit level and more stability [25–27]. Moreover, an upgrade of AC lines into DC ones implies minor infrastructure changes and increases the transmission capacity [24]. In this sense, there are several examples of HVDC installations in different countries (Table 4) [26, 28]. Their locations can be found in Fig. 3. There are remarkable ones like the Rio Madeira in Brazil (Fig. 3, 3), which is the longest HVDC installation built ever (2375 km) [29]. Jinping-Sunan ± 800 kV ultrahigh voltage direct current (UHVDC) installation, in China (Fig. 3, 33) is the most powerful transmission line in the world, with a rated capacity of 7.2-7.6 GW [29]. More examples of HVDC installations can be found in many other countries such as USA, India and Canada, and their number is continuously increasing due to, among other reasons, the multiple advantages that offers HVDC for power transmission in long distances (> 800 km for overhead lines and > 50km for cable systems).

Data collected about the amount of HVDC installed in last years, shows an annual linear increase in number of installations and an exponential growth of the installed power(Fig. 4). Table 5 compares the performance of the two transmission technologies [26]. The table also shows that DC transmission systems are more cost effective than AC ones for long distances, and they overcome some drawbacks presented in AC transmission systems, such as maintenance of synchronism, need of line compensation and high ground impedance. Thus, DC transmission systems are more suitable than AC transmission systems in applications that require transmission of power over long distances, such as underground and underwater cables. However, nowadays tapping microgrids to HVDC or medium voltage DC (MVDC) systems is a technical challenge.

4. Point of common coupling (PCC): interconnection between the mains grid and the microgrid

Microgrids are connected and disconnected from the mains grid at the PCC (Fig. 2 - 2). This interconnection is done through a switchgear, that can also be combined with power electronics. Three main types of switchgears are used: circuit breakers (CB), contactors and switches [30]. In microgrids, among the aforementioned types of devices, the preferred switchgear is the switch. In fact, recent researches on microgrids employ static switches with fast response or digital signal processor (DSP) [21]. These interconnection switches are designed to meet grid interconnection standards, reduce custom engineering and site-specific approval processes, and minimize the cost [14]. A study of the grid interconnection standards and guidelines for Europe and America can be found in [31]. Although, the study of microgrid interconnection can be simplified in medium voltage (MV) and low voltage (LV) networks [32]. LV switches are normally air insulated, meanwhile MV types are air, oil or sulfur hexafluoride (SF_6) insulated [30].

Some examples of microgrids interconnected to the mains grid only with switches (Fig. 2 - 2, 2a) can be found [14, 33–37]. However, this type of connection usually requires additional elements that isolate the microgrid from the mains grid. Those devices are transformers (Fig. 2 - 2, 2b) [14, 21, 38–50] and power converter (Fig. 2 - 2, 2c, 2e, 2g and 2i) [21, 51–53].

Table 5: Comparison between AC and DC transmission systems.

Issue	**AC**	**DC**
Transmission costs		
• Investment costs		
▹ Right-of-way (ROW)	Higher	Lower
▹ Towers	Higher	Simpler and cheaper
▹ Insulators	Higher	Lower
▹ Conductors	Higher	Lower
▹ Terminal equipment	Lower	Higher
• Operation costs		
▹ Losses	Higher	Lower
▹ Skin effect	Yes	No
▹ Dielectric losses	Higher	Lower
▹ Corona effects	Higher	Lower
▹ Compensation	By means of reactive power	Lower
Technical considerations		
• Control of transmitted power	Need of reactive power control	Full
• Transient and dynamic stability	Worse	Better
• Fault currents	Limited	Higher
• Power carrying capacity	Distance dependent	No distance dependency
• Voltage control	Load dependent	No reactive power (Q) control
• Line compensation	Yes	No
• Interconnection	Need of synchronism and large power oscillations	Asynchronous connection
• Ground impedance	High	Low
• Reliability	Similar	Similar
• Availability	Similar	Similar
Applications	Short distances ($<$ 50km)	Underground and underwater cables
		Long distance bulk power transmission
		Asynchronous interconnections of AC systems
		Stability of power flows in integrated power systems

Table 6 summarizes most of the possible interconnections between microgrids and the mains grid as a function of the type of current and voltage level. It also classifies the main topologies that can be used for PCC. Thus, Table 6 (blue text) comprises possible topologies for DC transmission (Fig. 2 - 2, 2d, 2f and 2h) with combinations for different voltage levels (back to back converters and matrix converters [54, 55], multilevel converters [56], modular multilevel converters [57], inverters [58] and non-isolated and isolated DC/DC converters [59].

The microgrid technology (AC or DC) is a key factor that must be considered in order to chose a proper interconnection switch. A mechanical switch does not open instantaneously, so there will be a short arc until the dielectric strength is enough to hold off the driving voltage. In an AC circuit, this interruption process is assisted by the fact that there is a natural 'current zero'. DC circuit do not have natural 'current zero', which implies that the switch must incorporate a mechanism to set the current to zero. As a result, the stress on the contacts are greater in a DC switch than in an AC one for the same voltage and current. Unless, sometimes it is feasible to use an overrated AC circuit breaker in DC systems, many applications requires the development of a specific DC breakers. Nowadays, this technical drawback can be overcome through commercial products for LV [60] and MV microgrids [61]. Nevertheless, solutions for AC systems are still more economical.

5. Distribution

Microgrids can be classified into AC and DC microgrids based on the characteristics of the distribution line (Fig. 2 - 3). There are also hybrid microgrids that combine AC and DC distribution lines that are controlled separately [69–72].

AC microgrids can present different distribution types: single phase (Fig. 2 - 3, 3a)), three phase without neutral (Fig. 2 - 3, 3b) and three phase with neutral (Fig. 2 - 3, 3c).

In DC microgrids, there are three main types of distribution: monopolar (Fig. 2 - 3, 3d), bipolar (Fig. 2 - 3, 3e) and homopolar (Fig. 2 - 3, 3f) [9, 52]. There are also some DC microgrids with multiple buses in order to obtain higher reliability [73]. Due to the fact that there is no reactive power (Q), DC distribution presents several advantages, such as reduction of the power losses and voltage drop, and an increase of capacity of the electrical lines. [6]. Therefore, its planning, implementation and operation is simpler and less expensive. A comparison between AC (single-phase and three phase) and DC (monopolar and bipolar) distribution lines in terms of resistances, cable sections and conductor material could be found in [74]. It concludes that DC bipolar transmission is the best option. Furthermore, the studies presented in [75, 76] show that, in the same conditions, DC transmission lines can transmit more power. Thus, the DC alternative allows a bigger extension of the network for the same load, and provides a reliable and high-quality power distribution [77].

Taking into account all the aforementioned facts, it can be said that DC distribution has more advantages compared with AC distribution. However, DC distribution lines have only been used for special applications, such as telecommunication systems, vehicles, ships and traction systems [78]. Important research efforts are being carried out in order to include DC distribution lines in buildings. USA has several examples of this type of installations (Table 7) [79].

The microgrid availability is an issue directly related with the type of distribution. There are few research papers that deal with the availability of AC and DC microgrids. In [80] AC and DC power systems are compared in terms of reliability, overall feeding efficiency, scalability and maintainability. The analysis in terms of reliability is carried through the comparison of two AC

Table 6: Power converters topologies for the PCC (Fig. 2): topologies in real and experimental microgrids (black) and proposed topologies (blue).

GRID \ MG		MV AC	MV DC	LV AC	LV DC
HV	**AC**	2b[10] Transformer [62] 2e[10] Transformer and back to back converter or matrix converter	2i[10] Transformer and inverter 2d[10] Multilevel inverter and modular multilevel inverter	-[11] -[11]	-[11] -[11]
	DC	2d[10] Multilevel inverter and modular multilevel inverter 2f[10] Inverter and transformer	2h[10] Multilevel converter and modular multilevel converter	-[11] -[11]	-[11] -[11]
MV	**AC**	2b[10] Transformer [63] 2c[10] Back to back converter and matrix converter 2e[10] Transformer and back to back converter or matrix converter	2g[10] Multilevel inverter and modular multilevel inverter 2i[10] Transformer and rectifier	2b[10] Transformer 2e[10] Transformer and back to back converter or matrix converter	2d[10] Multilevel inverter and modular multilevel inverter 2i[10] Transformer and inverter
	DC	2f[10] Inverter and transformer 2d[10] Multilevel inverter and modular multilevel inverter	2h[10] Multilevel converter and modular multilevel converter and isolated and non isolated DC DC power converters	2d[10] Multilevel inverter and modular multilevel inverter 2f[10] Inverter and transformer	2h[10] Multilevel converter and modular multilevel converter
LV	**AC**	2b[10] Transformer 2e[10] Transformer and back to back converter or matrix converter	2i[10] Transformer and inverter 2d[10] Multilevel inverter and modular multilevel inverter	2a[10] No power device [14, 33–37] 2b[10] Transformer [14, 21, 38–50] 2c[10] Back to back converter [51, 53, 66–68]	2g[10] Inverter [64] 2i[10] Transformer and inverter [52, 65]
	DC	2d[10] Multilevel inverter and modular multilevel inverter	2h[10] Multilevel converter 2h[10] Modular multilevel converter	2d[10] Inverter 2f[10] Inverter and transformer	2a[10] No power device 2h[10] Isolated and non isolated DC DC power converters

[10]Numbers referred to Fig. 1.

[11]Not possible combination.

Table 7: Examples of DC distribution systems in USA.

Country	State	Location
USA	California	CA Lightning Tech Center & UC Davis Campus (Davis)
		Southern Cal Edison, Utility Services Office (Irwindale)
		LA Community College, Trade Tech Campus (Los Angeles)
		Johnson Controls, Headquarters Office (Milwaukee)
		UC San Diego, Sustainability Center (San Diego)
	Michigan	Optima Engineering, MEP firm (Charlotte)
	Michigan	Nextek Power, NextEnergy Center (Detroit)
	Pennsylvania	PNC Financial, Headquarters Office (Pittsburgh)
	Texas	Lauckgroup Architectural Office (Dallas)
	Washington	US Green Building Council, Conference Rooms (Washington DC)

and DC models, and it concludes that the reliability obtained in DC power systems is about two orders higher than the one reached in AC power systems. In the same manner, DC microgrids availability is affected by the circuit topology design choices for the power electronic interfaces between the DGs and the rest of the microgrid [81].

6. Protection schemes

The design of protection schemes for AC and DC microgrids (Fig. 2 - ④) is a challenging task because there are several parameters involved, such as the dynamic structure of the microgrid, different levels of current of the devices, etc. Protections must be designed based on the following parameters: sensitivity, selectivity, speed of response and security level [9]. Among all these parameters and issues, the protection scheme is basically derived from two: the number of the installed DGs, and the availability of a sufficient level of short-circuit current in an islanded operating mode of the microgrid [9, 82].

Several protection schemes (Fig. 2 - ④) have been developed for AC microgrids [9, 83–87], they can be classified into centralised and decentralised schemes. On decentralised schemes each DG provides its own relay, which is an efficient technique against line-to-ground and line-to-line faults but limited to faults with low impedance [9]. On the other hand, centralised methods are based on a voltage protection scheme and require a central protection unit in the MGCC [9].

The protection scheme for DC microgrids (Fig. 2 - ④, 4b) requires a different approach because it faces different challenges, mainly the immaturity of standards and guidelines, and the limited practical experience [88]. Moreover, a common objection against the application of DC in power systems is that the current in DC systems does not have any natural zero crossing [89, 90], thus, short-circuit current interruption is more difficult to obtain than in an AC system. However, low-voltage DC system can use AC breakers if the ratings are adjusted to the correction factors that manufactures provide [90]. For this reason, it is interesting to identify which are the principles of AC system protection that may be applied, and whether it is enough a conventional AC system protection. Nowadays, there are several protection devices available on the market for LV DC systems, that comprehend fuses, CBs, molded-case CBs (MCCB), LV power CBs, and isolated-case CBs. In [60] a protection scheme for DC microgrids that uses mostly commercial DC protection devices is proposed. Another example can be found in [91], which proposes a design framework for DC microgrids that aims to optimize the protection scheme on the basis of

Table 8: Examples of protection schemes for AC and DC microgrids.

Type	Protection strategy	Operation	Communication link
AC	• Adaptive	Both	Yes
	• Based on communication-assisted digital relays	Both	Yes
	• Voltage	Islanded	Yes
	• Harmonic content	Islanded	Yes
	• Current travelling waves	Grid-connected	No
	• Distance	Both	No
DC	• Based on commercial DC protections	Both	No
	• Optimal unit and non-unit protection	Both	Yes

economic issues. Table 8 summarises the principal protection schemes proposed in literature for both AC and DC microgrids [9, 60, 86, 91–93].

Protection schemes must also include ground fault detection and isolation mechanisms to ensure system safety [88]. Grounding methods for AC and DC low voltage and medium voltage drive systems can be classified into solidly grounded, low-resistance, high-resistance and ungrounded systems [94]. Unless there is a noticeable research and practical experience with ground fault detection and isolation in AC systems, DC systems still require further research and innovation, specially for DC microgrids [88].

7. Monitoring and measuring system

Microgrid monitoring system (Fig. 2 - 5) must perform several tasks and must fulfil certain requirements: distributed structure to monitor each unit simultaneously, online definition and modification of system configuration and remote control and monitoring of the whole system, among others [95, 96]. The available literature proposes a wide range of monitoring schemes for microgrids [95, 97–102]. The following alternatives can be highlighted:

- A framework based on the service-oriented architecture (SOA) model [98]. A SOA can be defined as a component model that interrelates different functional units of an application, called services, through well-defined interfaces and contracts between services.
- Installation at each component of the microgrid universal monitoring, protection, and control units (UMPCUs) [99]. These units are similar to intelligent electronic devices (IEDs). They collect data about connectivity, device model and measurements.

There are vendors that supply commercial solutions for monitoring and control of microgrids [103]. It is also possible to monitor microgrids through phasor measurement units (PMU), as it has been proposed in [104]. These PMUs are systems which offer more accurate data about the power system, which allow to manage the system more efficiently and with a higher level of response [105].

Therefore, the main difference between AC and DC microgrids is that DC ones only require to monitor and control a reduced number of variables. In fact, monitoring systems for DC microgrids (Fig. 2 - 5, 5b) are simpler than AC microgrids (Fig. 2 - 5, 5a) because they do not require to monitor the frequency nor the reactive power.

8. Power converters

The three main components of a microgrid (DGs, SSs and loads) are connected to it through power converters (Fig. 2 - 6). These power converters rely on the type of microgrid (AC or DC), as well as on other features of the devices (voltage levels, power flow direction, etc.). In addition, they usually include a transformer in order to obtain galvanic isolation.

Tables 18 and 19 summarize the main topologies of isolated power converters used in DGs and SSs for coupling to AC grids (Fig. 2 - 6, 6a and 6b) [106, 107]. Both tables show that power converters usually require a controlled inverter, which is composed of insulated-gate bipolar transistors (IGBT) and capacitors on the DC bus. Matrix converters can also be used, which guarantee bidirectional power flow by means of bidirectional switches and without any significant reactive component [108].

Since DC grids are not yet widespread, there are no standard topologies of power converters to couple DERs to them. Tables 18 and 19 present some feasible power converters architectures for coupling DGs and SSs to DC microgrids (Fig. 2 - 6, 6c and 6d) [59, 107, 109–111]. Both tables show that power converters usually require fewer components in DC lines than in three-phase AC lines. Some of DC topologies can also use high-frequency transformers, which implies that they are smaller and lighter than the low-frequency transformers of AC microgrids.

The efficiency of the power converter is a key parameter. It depends on many variables, such as power rate, load rate, core volume and material when galvanic isolation is needed [112]. The majority of power converters have optimal efficiency when they work at their nominal power. In [113] an approach for comparison of system conversion efficiencies for residences is presented. This work concludes that the total conversion efficiency in residential distribution lines increases in case of AC lines and decreases for DC lines. However, if the power source of a residence is a fuel cell or another DC generator, the total conversion efficiency within a residential DC distribution system could be similar or better than for AC distribution. Another study [114] shows that AC and DC distribution systems can have similar efficiencies if the following conditions are met: loads are equal in ratio, and an AC source supplies the AC power and a DC source supplies the DC power. The work in [115] studies the efficiency of DC systems. Among other conclusions, it states that, under the assumption that semiconductor losses decrease by half, the efficiency of a pure DC system becomes higher than AC system. Moreover, [116] concludes that the current ripple (or harmonics in the AC cases) is reduced in the DC case due to two facts: the AC/DC circuit inside most devices acts only as a reverse polarity protection, and the ripple caused by different devices is not synchronized. Thus, it can be said that the efficiency of power conversion is normally higher in DC systems, and it is mainly affected by the technology of the primary source and the AC and DC load ratios.

9. Control

AC and DC microgrids require different control tasks (Fig. 2 - 7) in order to guarantee a correct operation of the system. Normally, a hierarchical control carries out these tasks. There are three levels of controls are described from the outer to the inner level of control as follows (Fig. 5) [22]:

- *Grid level.* At this level a distribution network operator (DNO) and a market operator (MO) are found. Active management techniques in microgrids allow DNO to take advantage of a several control variables which are not considered in their current operation and planning philosophies [117]. The MO is in charge of the participation of the microgrid in energy markets and it can follow different market policies such as serving the total demand of the microgrid using its local production or participating in the open market buying and selling active and reactive power to the grid [118].

- *Management level*. A MGCC performs those tasks related to the management of the microgrid. The main functions of the MGCC are the restoration of the frequency (only in AC microgrids) and voltage, synchronism between the microgrid and the grid (only in AC microgrids), load shedding and optimization of the production of the microgrid [119].

- *Field level*. One local controller (LC) is placed in each element of the microgrid (DGs, SSs or loads). According to the type of element (DG, SS or load), the corresponding LC carries out different tasks:

  - *LC for DGs* (Fig. 2 - 7, 7a and 7b). The best alternative for controllable DGs, such gas turbines, small diesel generators, ect., in which the primary energy is controllable, is the droop control [22, 117, 120–125]. This control method offers a high reliability and does not require communications between DERs. Several variations of this method that overcome its drawbacks can be found in literature [43]. For non-controllable DGs, in which the primary energy is not controllable, such as wind turbines, PV, etc., non linear droop control [126] and hybrid droop control with maximum power point tracking (MPPT)can be used [127–129].
  - *LC for SSs* (Fig. 2 - 7, 7c and 7d). SSs need specific charge/discharge control strategies. In [130–132] the proposed control method is the state of charge (SoC)-based adaptive droops. In addition, for an optimal operation different control techniques as a function of the SS technology used are proposed in [107].

    In this control level the islanding detection is carried out in DGs and SSs, which guarantees their good performance both connected or disconnected from the mains grid. There are several islanding detection techniques for AC lines that can be classified into local and remote detection techniques [133–135]. All these techniques are based on measuring different magnitudes (voltage amplitude, frequency, phase and harmonics). However, in DC systems only voltage can be measured, so new islanding detection techniques must be developed. There are few works that deal with this issue [136] so more research efforts are needed.
  - *LC for Loads*. If a centralised hierarchical control is used, load shedding is controlled by the MGCC. In case of agents based control, an agent is placed in each load in order to perform its control.

Both DNO and MO functions are done at the mains grid level, while MGCC is located in a central computer, and the local controllers are placed in power converters coupled to each element of the microgrid (DGs, SSs or loads). This hierarchical control can be carried out in a centralised or decentralised manner, which is commonly called multi-agent based control (MAS). The centralised control alternative offers the possibility of implementing a basic management system with low costs of installation and operation. On the other hand, MAS control provides plug and play performance at expense of a more complex control design [43].

DC microgrids present the advantage that there is no need for controlling frequency nor reactive power. In this manner, the control tasks are simplified since the devices can be connected to the microgrid directly, without any process of synchronism. Therefore the connection of the microgrid to the mains grid is done asynchronously and only the flow of active power must be controlled. On the other hand, in AC microgrids frequency must be controlled and the devices must be synchronized before their connection with the microgrid, and the microgrid must be synchronized with the mains grid before its connection. A summary of the main synchronization methods can be found in [137], which are mostly based on phased-locked loops (PLL). Furthermore, reactive power flow must be also controlled in the PCC, which adds complexity to the whole control. There are DC and AC cases that also require voltage balancing. In three-phase AC microgrids, voltage balancing can be carried out in several manners: introducing special control loops to converter based DGs and SSs, using reactive support devices such as static var compesators (SVC) or static synchronous compesators (D-STATCOM) with appropriate control and using simple switched capacitors [138]. For DC microgrids with bipolar or homopolar distribution, voltage balancing must also be carried out. For this purpose, voltage balancers can be placed near the power converters in order to balance the distribution lines [52]. In Table 9 a summary of the principal tasks that must be carried on in each kind of microgrid is shown [9, 43, 139, 140].

9.1. Stability

If the sources of a microgrid are controlled by means of local measurements, stability becomes a critical issue [141]. When investigating the stability of a microgrid, both the generation dynamics and the load dynamics must be considered [142]. The largest body of work done in microgrid stability analysis is for radial microgrids while stability studies for meshed microgrids are still an open research area [141].

Several stability studies for AC microgrids can be found in [141, 143–146]. The aforementioned studies lead to conclude that the stability is mainly affected by the frequency-droop coefficient, and it is usually improved by means of a good design of the droop coefficients and a droop control with adjustable dynamic behaviour [146]. The classification of the stability issues in microgrids presented in [143] uses that of a large power system. Based on this, Table 10 summarizes the criteria and different methods for stability improvement on AC microgrids. It can be said that the stability of AC microgrids is mostly influenced by the mode of operation (connected or disconnected from the mains grid), control topology, types of DERs and network parameters. In addition, the target application and the system scenarios influence the efficacy of the stability improvement methods.

In DC microgrids the stability issues are inherently related with the need of power electronics interfaces for integrating sources, loads, and energy storage devices [147]. There are many works that deal with the small signal stability in DC microgrids [131, 147–151]. Taking all these works into account, it can be said that constant power loads introduce voltage oscillations into the microgrids that can be overcome by means of hardware solutions (increasing system's capacitances or resistive loads, reducing system's inductances and load shedding) or control strategies (linear and boundary controllers).

9.2. Modelling

Modelling microgrids is a key step in order to obtain a suitable control. Table 11 summarizes models for AC microgrids proposed in [147, 152, 153]. As it is shown, most of the models employ droop control, consider constant power loads and analyse the microgrid both connected and disconnected from the mains grid. Few models consider three phase systems and there are

Table 9: Control tasks in the hierarchical control for AC and DC microgrids.

Hierarchical level	**Controller**	**Control tasks**	**AC**	**DC**
Grid level	DNO	• Control of multiple microgrids	✓	✓
		• Control of the active power flow between the microgrid and the grid	✓	✓
		• Control of the reactive power flow between the microgrid and the grid	✓	✗
	MO	• Market functions of each specific area	✓	✓
		• Economical concerns in the optimal operation of the microgrid	✓	✓
Management level	MGCC	• Connection and disconnection of loads from the microgrid	✓	✓
		• Restoration of the nominal voltage of the microgrid	✓	✓
		• Monitoring the microgrid	✓	✓
		• Smooth connection between the microgrid and the grid	✓	✓
		• Island detection and reaction	✓	✓
		• Synchronization with the main grid	✓	✗
		• Restoration of the nominal frequency of the microgrid	✓	✗
		• Voltage balancing	✓[12]	✓[13]
Field level	LC of DGs	• Sharing of active and reactive loads	✓	✓
		• Control of the voltage and frequency of the microgrid during island mode	✓	✓
		• Smooth transient from voltage to current source and viceversa	✓	✓
		• Inner control: voltage sags, harmonics, control reference matching and flicker	✓	✓
		• Sharing of non-lineal loads	✓	✓
		• Islanding detection and reaction	✓	✓
		• Operation as FACT units	✓	✗
		• Synchronization with the microgrid	✓	✗
	LC for SSs	• Storage level control	✓	✓
		• Decision of charging or discharging	✓	✓
		• Voltage regulation	✓	✓
		• Frequency regulation	✓	✗
		• Islanding detection	✓	✓
		• Synchronization with the microgrid	✓	✗
	LC for loads	Normally no local control, load shedding managed by the MGCC or by agents	✓	✓

[12] Only in three-phase systems.

[13] Only in bipolar and homopolar systems.

Table 10: Main stability issues and reasons and their corresponding possible improvement methods for AC microgrids.

Issues	Reasons	Improvement methods
Small signal stability	Feedback controller	Supplementary control loops
	Small load change	Coordinated control of DGs
	System damping	Stabilizers for DGs
	Power limit for DGs	Energy management system (EMS)
Transient stability	Islanding	Control of storage
	Loss of DG	Load shedding methods
	Large load step	Protection device setting
	Fault	Control of power electronics
Voltage stability	Reactive power limit / Current limiters	Reactive compensation
	Load dynamics (induction motors)	Load shedding
	Under voltage load shedding	Modified current limiter for microsources
	Tap changers and voltage regulations	Voltage regulations with DGs

some models include SS systems which helps studying in detail dynamics and possible situations on a microgrid. According to software tools for modelling microgrids, *HOMER* has been the most extended energy modelling tool. There are other tools suitable for microgrids modelling, such as *EADER*, *DER-CAM*, *Matlab-Simulink* and *PSCAD/EMTDC* [154, 155].

There are few works that deal with the modelling of DC microgrids. Nevertheless, simple DC microgrid models can be found when analysing their stability [131, 147–151]. Although, most of them do not consider control schemes and only take into account RLC devices.

9.3. Power quality

Renewable energy systems have many benefits for energy safety and environmental impact. However, the integration of intermitent power sources in the grid and its power quality is a technical challenge that must be cope with [19]. Some solutions have been proposed in order to improve power quality in AC microgrids [155]. DC distribution networks ensure a higher power quality to the customers than in AC distribution network and facilitates more DGs connection [9]. The results of ongoing research on the field of DC microgrids indicate a significant reduction in power quality problems, losses and downtime and protection malfunctions [9].

Thus, there is ongoing research to find out the details of DC microgrids which result in significant reduction in power quality problems, losses and downtime and protection malfunctions [9].

9.4. Optimization

Optimal control of microgrids is an active field of research whose most common objective is to minimize the operating cost [156]. Some of the solutions proposed only consider the electrical generation of microgrids and include mathematical programming, heuristics and priority rules [156]. However, there are also some microgrids, most of them residential microgrids, that also include thermal generation which must be also considered. In [157] there are examples, most of them residential, of such models of microgrids in order to achieve an optimal thermal generation.

Optimization of AC microgrids has been widely studied and related works deal with different issues:

- Load demand and environmental requirements [157]. In this work, a model to determine the optimum operation of a microgrid with respect to load demand and environmental requirement is constructed.

- Sustainability [158]. The sustainability of a microgrid is improved through the minimization of carbon emissions and at reducing production costs and maximizing quality in this work.

- Economics [159–161]. Some works propose different solutions in order to economically optimize different issues in microgrids. A hierarchical control that deals with an economic optimization in the second level of the architecture is presented in [159]. Another proposal can be found in [160] where optimization techniques and management functions are implemented in a central energy management system (CEMS). This CEMS is aimed at optimizing the economic exploitation of the microgrid in grid-connected mode and it also improves the reliability of the microgrid in islanding operation. In [161] a methodology to design the number and capacity for each component in a microgrid with combined heat and power (CHP) system is presented that minimizes the annual cost.

Table 11: AC microgrid models proposed in literature.

Model	Distribution	DG	SS	Loads	Mode	Control
• Admittance matrix	Three-phase	Constant power	No	Constant power	Both	Droop
• DC source with non-linear equations that are linearised	Single-phase	First order transfer functions	No	RLC circuit	Both	Droop
• DC source with equations in state-space	Single-phase	DC source and VSC	No	RLC circuit	Island	Droop
• State space in a common reference frame and linearisation	Single-phase	DC source and VSC	No	Constant power	Both	Droop
• State space in a common reference frame and linearisation	Single-phase	Synchronous generator based DG and power	No	Constant power	Both	Droop
• Small signal analysis	Single-phase	Non-linear equations	First order transfer functions	Constant power	Island	-[14]
• Multilevel type control and management scheme supported by a communication infrastructure	Single-phase	Dynamic model based on the characteristics of each type of generator	Constant DC voltage sources coupled by power electronics devices	Two types: constant impedance and motor loads	Both	Droop
• Electrical equations in admittance form	Three-phase	Coupled by inverter droop	Coupled by inverter droop	Coupled by inverter droop	Both	Droop
• System matrices based on four defined complex vectors	Single-phase	Coupled by power electronics and two types: active and reactive power regulated and voltage-frequency regulated	No	No	Both	Droop
• Based on hub model	Single-phase	Energy hub model	energy hub model	Constant power	Island	-[14]

[14]No control considered.

- Design of different controllers, filter, and power sharing coefficients [162]. Linear and nonlinear models of a microgrid operating in grid-connected and autonomous modes are presented in this work. Through these models, an optimization problem is formulated for dealing with the design of controllers, filters and power sharing coefficients.
- Fuel consumption [163, 164]. In [163] an algorithm that performs an optimization of fuel consumption and emissions costs of microsources using a heuristic approach is presented. Another proposal can be found in [164] where the fuel consumption rate of the system is reduced guaranteeing the local energy demand (both electrical and thermal) and providing a certain minimum reserve power.
- Production of local DGs and power exchanges [118]. A central controller aims to optimize the operation of the microgrid during interconnected operations by means of the optimization of the production of the local DGs and power exchanges with the main distribution grid.

There are very few examples of DC microgrids that propose optimal solutions for their management. In [165] both the allocation and sizing of internal source converter storage were studied in order to identify the topology characteristics that can be applied more generally to DC microgrids. Another proposal for hybrid AC/DC microgrids can be found in [166]. This work formulates a multi-objective optimization problem that allows to optimally operate hybrid AC/DC microgrids, minimizing their energy costs and greenhouse gas emissions.

10. Regulatory issues

A regulatory framework must include a set of principles, rules and incentives, which address both technical and economic issues [167]. The regulatory environment for microgrids (Fig. 2 - 8) is complex since it combines multiple existing regulations that have not been specifically devised for microgrids [168]. Moreover, the most cited restriction to interconnect microgrids with the distribution network is the high connectivity cost in the distribution network due to high connection fee policies [167]. Islanding also creates conflict with the existing grid codes and regulations. Another important issue is the metering since netmeter with bidirectional registering capability needs to be installed at the PCC by means of metering tools that support the participation of microgrids in the market [167].

Therefore, it is necessary to establish a suitable framework, adapted to each country, for the development and proliferation of microgrids. In Europe, for instance, the whole interconnection framework needs a revision that must take into account specific issues such as the change of characteristics according to the mode of the microgrid (connected or islanded), protections and communication infrastructure [168]. In Japan, the Ministry of economy, trade, and industry (METI) has already established rules and technical guidelines for grid interconnection. However, it is still necessary to unify worldwide the standards required for interconnecting distributed generators with information and distribution networks [168]. In this line, in the United States the IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems 1547 establishes criteria and requirements for the interconnection of distributed resources with electric power systems. Its section 1547.4 is being treated as the fundamental standard for microgrid standardisation [43].

For AC microgrids some of the existing standards for DERs can be adapted (Table 12). This is not possible for DC distribution and there are several organizations engaged in developing standards. These organizations also support proof of concept sites to benchmark the needs of DC distribution, such as IEC, EMerson, etc. [169, 170]. There are also many groups working on the topic, which are developing several voltage and performance standards. Among these standards, there are three that must be highlighted: EN 300 132-3-1 of ETSI, Emergence Alliance standard for 380 Vdc and IEC SG4 for LV distribution [169]. The last standard proposes a DC-powered home (Fig. 6) [171]. Table 12 provides a summary of the existing standards for both AC and DC microgrids [43, 169].

11. Economic analysis

An economic analysis of microgrids can be carried out by means of the study of the relevant benefits and costs. Two main issues are considered: on-site generation from the customer perspective and the traditional utility economics of expansion planning from the utility perspective [168]. In this sense, the main benefits are an increased reliability for microgrid participants, general reliability improvements, waste heat recovery and generation adequacy [167, 172, 173]. Some models to quantify these economic benefits can be found in [174].

Besides, the costs can be divided into microgrid development costs and the costs related to the DNOs (Fig. 7) [172]. The first set of costs (most relevant costs [90]) is related to microgrid development, which involves specific investment in controllers, protection devices, storage systems, installation, etc., and operation and maintenance expenditures (staff, losses on storage systems, maintenance of the equipments, etc.) (Fig. 7) [172]. Therefore, operating cost of microgrids under optimal control highly relies on microgrid configuration, optimization method and benchmark model [156]. The second set of costs is related to the DNOs expenses that may result from potential investment requirements in order to overcome technical problems, such as excessive voltage regulation, fault levels, voltage unbalance, and overloading (Fig. 7). Most of the time, these costs can be neglected since some studies show that significant quantities of microgeneration may be connected to distribution networks without significant investments [172], thus, they are not considered in this work. The following items describe the development costs considered in AC and DC microgrids:

- Since AC technology is more mature than DC technology, the development and production costs (Fig. 7) of customized components are usually higher for DC microgrids. However, it has to be taken into account that the design of the control and metering system for DC microgrids is simpler than for AC microgrids (no control of reactive power, no synchronization control and no frequency control).

- Installation costs in AC and DC are determined by the number of elements installed which are highly dependant on the features of the connected elements (DGs, SSs and loads). Therefore, DC microgrids lead to lower installation costs in feeding offices or data centres since they tend to have more DC loads. Offices or data centres fed with DC microgrids have lower installation costs, since they tend to present more DC loads. R1.2 DC microgrids have been also proposed for feeding trains and electrical bycicles in a clean and reliable manner [175, 176]. Besides, AC microgrids are more suitable to feed factories or big plants, because in these installations more AC loads are presented.

  R1.1 According to domestic applications, a variety of both AC and DC loads are presented in a current home. In Table 14, a summary of the power stages, internal loads and the power consumption that usually present the main home appliances are presented. As it is

Table 12: Applicable standards to AC and DC microgrids.

Type	Standard	Description	Scopes
AC and DC	IEEE 1547	Criteria and requirements for interconnection of DERs with the main grid	• 1547.1 Conformance test • 1547.2. Application guide • 1547.3. Monitoring and control • 1547.4. Design, operation and integration of DERs • 1547.5. Interconnection guidelines for electric power sources greater than 10 MVA • 1547.6. Interconnection with distribution secondary networks • 1547.7. Distribution impact studies for interconnection of DERs • 1547.8. Recommended practice for establishing methods and procedures
AC	EN 50160	Voltage characteristics of electricity supplied by public distribution networks	• Definitions and indicative values for a number of power quality phenomena in LV and MV networks • Limits for power frequency, voltage variations, harmonics voltage, voltage unbalance, flicker and mains signalling
	IEC 61000	General conditions or rules necessary for achieving electromagnetic compatibility	• Safety function and integrity requirements • Compatibility levels • Emission and immunity limits • Measurement and testing techniques • Installation guidelines, mitigation methods and devices
	IEEE C37.95	Protective relaying of utility-consumer interconnections	• Establishment of consumer service requirements and supply methods • Protection system design considerations
DC	ETSI EN 300 132-3-1	Environmental engineering (EE), Power supply interface at the input to telecommunications and datacom (ICT) equipment; Part 3; Subpart 1: Direct current source up to 400 V	• Definition of DC interface up to DC 400V • DC bus voltage limits consideration • Guidelines for testing powered equipment behaviour for abnormal operating conditions and stress
	EPRI and Emergence	Standard for 400 Vdc in buildings (*under construction*)	• Interiors and occupied spaces where lighting and control loads dominate the need for DC electricity • Data centers and telecom central offices with their DC-powered information and communications technology equipment • Outdoor electrical uses, including electric vehicle charging and outdoor light-emitting diode (LED) lighting • Building services, utilities, and HVAC with variable-speed drive and electronic DC motorized equipment
	IEC SG4	LVDC distribution system up to 1500 V (*under construction*)	• Align and coordinate activities in many areas where LVDC is used such as green data centres, commercial buildings, electricity storage for all mobile products (with batteries), electric vehicles, and so forth, including all mobile products with batteries, lighting, multimedia, ICT etc. with electronic supply units • Measuring methods • Architecture: 100 % DC or hybrid • Grounding • Operation and life cycle of the equipment • Protective measurements for hazards for LVDC distribution systems • The impact of DC (corrosion, insulation, etc.)

Table 13: Development costs in AC and DC microgrids.

Device	**Localization**	**AC**	**DC**	**Reasons**
Protections in PCC	Fig. 2 - 2	Lower	Higher	Technology more mature and lower power ratings in AC systems
Distribution	Fig. 2 - 3	Higher	Lower	Due to skin effect, reactive power etc. higher losses in AC systems
LV protections	Fig. 2 - 4	Lower	Higher	Lower power ratings and more mature technology in AC systems
Metering	Fig. 2 - 5	Higher	Lower	More variables to be monitored in AC systems
Communication	Fig. 2- 5	Similar	Similar	Depending to the control technique used
Power converters	Fig. 2 - 6	Higher	Lower	Lower efficiencies and more components in AC systems
MCC	Fig. 2 - 7	Higher	Lower	More tasks (synchronism, reactive power control, etc.) in AC systems
LC	Fig. 2 - 7	Higher	Lower	More tasks (synchronism, reactive power control, etc.) in AC systems
Load controller	Fig. 2 - 7	Similar	Similar	Similar tasks in AC and DC systems.

shown, a great part of these appliances presents AC/DC and DC/AC internal power stages. However, electronic devices such as TVs and PCs only present AC/DC power stages since they only have internal DC loads.

Homes can be fed by AC or DC microgrids in order to take advantage of the local energy resources. If homes are fed by AC microgrids, no change at the home appliances is necessary since they are all prepared for AC sources. In case of feeding homes by DC microgrids, two options can be considered. The first option is to design a DC distribution system inside the house (Fig. 6), obtaining a distribution system more reliable than AC distribution system. Besides, this option allows removal of several power stages inside the home appliances since the AC/DC stage would not be necessary. Removing the AC/DC power stage from all the home appliances involves a higher efficiency and saving costs for manufacturers. These saving costs rely on the characteristics of each home appliance and each manufacturer. The second option is to install an inverter at the entrance of the house in order to maintain an AC distribution line inside the house (Fig. 1). In this case, the unique cost involved would be this inverter, which rated power corresponds to the contracted power of the house. In Table 15 some examples of commercially available inverters are presented considering an average power of 5 kW at home.

- Protection costs. LV and MV protection devices are available for both AC and DC lines. AC technology has still more attractive prices even though DC technology has progressed.
- The operation costs are the result of the activity of the microgrid and include losses in storage systems, staff, etc. [177]. As it has been commented on section 5, if DC lines are compared with AC microgrids, they present lower power losses and, thus, lower operation costs.

Table 13 summarizes the aforementioned costs and provides a comparison between AC and DC

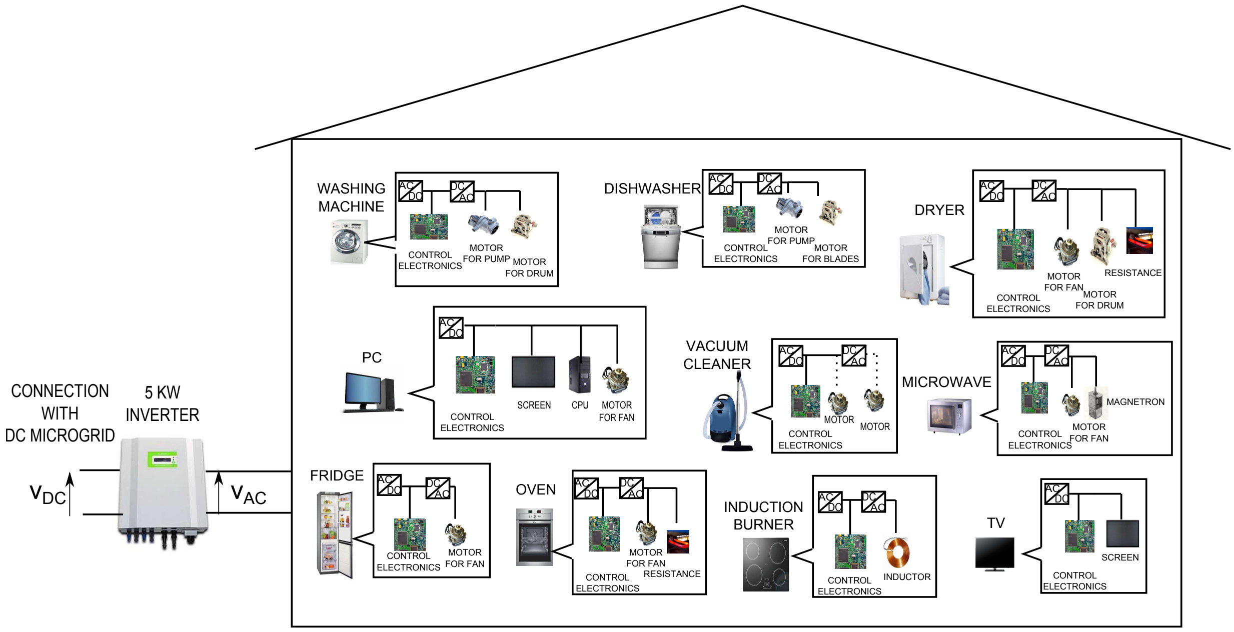

Figure 1: R1.1 Home feeded by a DC microgrid with an internal AC distribution system.

microgrids.

12. Future research areas

As it has been demonstrated through this work, microgrids attract a great deal of attention and different projects about microgrids have been developed all over the world. In extensive and highly dispersed countries, such as Canada, USA and Japan, several organisms, such as Power Systems Engineering Research Center (PSERC), Consortium for Electric Reliability Technology Solutions (CERTS), and Consortium for Electric Reliability Technology Solutions (NEDO), respectively, feature microgrids into their research programmes. As an example, thanks to the Sendai microgrid, the power supply of one hospital and some laboratories in Fukushima was guaranteed after the serious earthquake in 2011, Fig. 8. In Europe there are also projects of microgrids, although smart grids are the preferred alternative. Off-grid microgrids require a special mention because they play an important role on rural electrification. Several examples of remote areas can be found in which islanded microgrids guarantee the power supply. The Antarctic Princess Elisabeth Research Station, for instance, is powered by means of an islanded microgrid completely based on renewable energies (Fig. 9) [178]. Tables 16 and 17 provide a summary of microgrids installed all over the world [21, 43, 122, 179]. As they show, microgrids can be found in all continents, specially in countries such as China, USA and Canada. Figs. 11(a) and 11(b) are obtained combining the information of Tables 16 and 17 with the technology used and the installed power in each microgrid [179]. The data of these Figs. highlights two facts: the number of AC microgrids and their rated power has increased linearly, except from 2005 to 2008, when it grew exponentially (Fig. 11(a)). There are few examples of DC microgrids before 2003, their

Table 14: R1.1 Power characteristics of the principal home appliances.

Appliance	Power stages		Loads		Power
	Topology I: AC/DC	**Topology II: DC/AC**	**AC**	**DC**	**(kW)**
Fridge			Motor		0.1 to 1.0
Dishwasher			Motors for the pump and blades		1.0 to 2.2
Washing machine			Motors for the pump and drum		0.3 to 3.0
Dryer		Inverter	Motor for the drum, motor for the fan and resistance		0.2 to 2.0
Oven	Rectifier with power factor correction		Resistance and motor for the fan	Control electronics and DC bus	0.5 to 4.0
Induction burner			Inductor		1.2 to 2.2
Vacuum cleaner			Motor[15]		0.5 to 2.0
Microwave		Inverter with high voltage transformer	Magnetron and motor for fan		1.0 to 1.5
TV[16]		-	-	Control electronics and screen	0.02 to 0.5
PC[16]		-	-	Control electronics, screen, CPU and fan	0.02 to 0.4

[15]This motor can be an AC motor or a DC motor.

[16]No AC loads.

Table 15: R1.1 Features of some commercial available inverters with a rated power output of 5 kW.

Manufacturer	Model	Power Output (kW)	Efficiency (%)	Price (€)
Sunways	NT5000	5.0	97.8	1850
Fronius	IG TL 50	5.0	97.7	1990
Ingeteam	SUN 5TL	5.0	97.0	1550
ABB	Power-One PVI	5.0	97.0	1800
Schneider Electric	Xantrex GT 5.0 SP	5.0	96.0	1990

installed number started to increase slowly since then, until their number grow exponentially, in the last few years.

Related to the subject of further developments, both AC and DC microgrids leave open research areas that must be taken into account:

- *Decentralised control* [9, 139]. Most of the existing microgrids around the globe present a centralised control [43]. This type of control is optimal for small microgrids in which all the elements share the same goals. As these elements present different needs and the microgrid gets more complex, the alternative of decentralised control becomes more suitable. Thus, additional research efforts are needed in order to develop the decentralised control.

- *Protections* [180]. Microgrids are able to operate connected or disconnected from the main grid at any time. This dynamic scheme complicates the design of the protection scheme which must guarantee a safe operation in any case. Although some protection schemes have been proposed, they are customized solutions that do not provide universal lines for any kind of microgrid.

DC microgrids also required specific research efforts in the following issues:

- *Bus selection* [139]. The bus selection procedure is based on switching mechanisms that can lead to unwanted voltage oscillations. Achieving a smooth bus selection requires an appropriate control approach and implementation. Nowadays, there are few works that deal with this problem [73], thus more research efforts are needed.

- *Standards* [170]. The standardization of AC microgrids has greatly advanced in the last years. DC microgrids, on the other hand, do not have yet a specific standard. Some organisms like EPRI and EmergeAlliance have already take the first steps into standardization of DC distribution lines.

- *Islanding detection techniques* [136]. Islanding detection is a key requirement for electrical safety and equipment protection. Islanding detection algorithms in AC systems are based on systems frequency and phase, parameters that are not present in DC lines. Thus, new methods for islanding detection in DC systems are required to guarantee the reliability of the system.

13. Conclusions

Microgrids have attracted a great deal of attention during last years due to the several advantages they report. Microgrids can be built with an AC or DC distribution system which defines

Table 16: Examples of microgrids in Africa and America.

Continent	Country	Place	Type		Fig.
			AC	DC	9
Africa	South-Africa	Lucingweni	✓	✓	1
	Morocco	Akkan	✓		2
	Senegal	Diaka Madina	✓		3
America	Brazil	Campinas		✓	4
		Chico Mendes	✓	✓	5
		Ilha Ferradura	✓		6
	Canada	Ascension island	✓		7
		Bella Cola	✓		8
		Boston Bar	✓		9
		Hartley Bar	✓		10
		Kasabonika Lake	✓		11
		Nemiah Valley	✓		12
		Ramea Island	✓		13
		Senneterre	✓		14
		Toronto	✓		15
	Chile	Tac island	✓		16
		Coyhaique	✓		17
	Mexico	San Juanico		✓	18
		Xcalac		✓	19
	USA	Kotzebue, Alaska	✓		20
		Wales, Alaska	✓		21
		California	✓		22
		Borrego Springs, California	✓		23
America	USA	Dublin, California	✓		24
		Marin County, California	✓		25
		Palmdale, California	✓		26
		San Diego, California	✓		27
		Santa Cruz island, California		✓	28
		29 palms, California	✓		29
		Florida		✓	30
		Miami, Florida		✓	31
		Hawaii		✓	32
		Woodstock, Minnesota	✓		33
		New Jersey	✓		34
		Albuquerque, New Mexico	✓		35
		Los Alamos, New Mexico	✓		36
		Rochester, New York	✓		37
		Forth Bragg, North Caroline	✓		38
		Columbus, Ohio	✓		39
		Arlington, Texas		✓	40
		Austin, Texas	✓		41
		Colonias, Texas	✓		42
		Waitsield, Vermont	✓		43
		Washington DC	✓		44
		Madison, Wisconsin	✓		45

Table 17: Examples of microgrids in Antarctica, Asia, Europe and Oceania.

Continent	Country	Place	Type AC	Type DC	Fig. 9
Antarctica	Antarctica	Ulsteinen Nunatak	✓		46
Asia	China	Hefei	✓		47
		Nanjing	✓		48
		Xinjiang	✓		49
		Tianjin	✓		50
		Xiamen		✓	51
	Hong Kong	Town island	✓		52
	India	Maharashtra	✓		53
		Uttar Pradesh	✓		54
	Japan	Aichi	✓		55
		Hachinoche	✓		56
		Kuroshima island	✓		57
		Kyoto	✓		58
		Miyako island	✓		59
		Sendai	✓	✓	60
	Korea	Changwon	✓		61
	Singapore	Pulau Ubin	✓		62
	Taiwan	Longtan	✓		63
	Turkey	Ankara	✓		64
Oceania	Australia	Newcastle	✓		65
		Kings Canyon	✓		66
		Queensland		✓	67
Europe	Germany	Kassel, Manheim Wallstadt	✓		68
	Denmark	Bornholm island	✓		69
	Finland	Hailuot	✓		70
	France	Compigne		✓	71
		Lyon	✓		72
	Greece	Athens, Kithnos island	✓		73
	Holland	Bronsbergen, Groningen	✓		74
	Ireland	Cork	✓		75
	Italy	Milan	✓		76
	Macedonia	Agria	✓		77
	Norway	Utsira	✓		78
	Portugal	Azores	✓		79
		Ilhavo	✓		80
		Porto	✓		81
	Spain	Derio	✓		82
		Seville		✓	83
	United Kingdom	Eigg island, Scotland	✓		84
		Manchester	✓		85
		Nottingham		✓	86

the main features, advantages and disadvantages of the microgrid. This article has presented a full description of microgrids. AC and DC technology in transmission lines has been described concluding that DC technology offers several advantages in comparison with AC technology, specially for long distances. The PCC in AC and DC microgrids has been also analysed. AC technology presents several advantages at the PCC and AC protections are more economical than DC protections.

After the PCC analysis, the AC and DC distribution lines have been studied. DC distribution lines have definitely more advantages than AC lines due to lower loses, lower cable sections and higher transmittable power. Therefore, although the vast majority of distribution lines use AC technology, the interest on DC distribution lines is increasing and nowadays several examples of DC distribution lines can be found. Microgrids also need a protection scheme in order to guarantee a safe operation. In this sense, several protection schemes for AC microgrids and a few for DC microgrids have been presented. Moreover, commercial solutions for DC protections are still more expensive than AC protections. Besides, there is considerable experience in ground fault detection and isolation in AC systems which is not the case in DC systems. Thus, research efforts are needed in terms of the design of the protection scheme in DC microgrids and protection units.

Monitoring AC and DC microgrids has also been analysed in this paper. From this perspective, the tools and schemes for AC microgrids can be simplified for their use in DC microgrids. DC microgrids present two main advantages it terms of monitoring: generally simpler topologies of power converters for coupling units to DC microgrids and normally a higher efficiency of the power conversion in DC systems. According to the control, centralised or decentralised hierarchical control is normally used for AC and DC microgrids. Most of the installed microgrids use centralised control since its design simpler and easier for small microgrids. Although, there is a growing interest in decentralised control since it offers a plug and play performance and it is more suitable in case of bigger microgrids. The stability is another issue that has been commented and has been widely studied for AC and DC microgrids. Similar control and hardware solutions have been proposed for both AC and DC microgrids. Besides, islanding detection methods for AC systems are widely studied but very few works deal with this issue in DC systems.

Different proposals for modelling AC microgrids have been found that generally consider single-phase distribution lines and both modes of operation (connected and disconnected from the main grid). Research efforts are needed in modelling DC microgrids. The power quality has been also studied in AC and DC microgrids, concluding that DC systems offer higher power quality. Several proposals of optimization methods for AC microgrids have been found that deal with different issues such as sustainability, fuel consumption and design of controllers. DC microgrids optimization, although, requires research efforts.

Efforts have been made in the last years in defining standards and guidelines for building AC and DC microgrids. This study shows that the normative for AC microgrids is more mature than for DC microgrids, but there are several companies and organisms currently dealing with this subject. Economic analysis of AC and DC microgrids is also an important point to be considered. The conclusion of this study is that the costs derived from customizing units and protections are lower for AC microgrids. The costs of controllers and metering systems are lower for DC microgrids. In order to reduce the installation costs, AC microgrids are more suitable for feeding installations with a high number of AC loads (factories, big plants, etc.) and DC microgrids more appropriate for offices and data centres which include more DC loads. Finally, the current situation of microgrids has been presented together with a summary of examples of installed microgrids all over the world. As results of the work carried out, some research areas have been identified which require further research and development, such as the decentralised control and protections for both AC and DC microgrids.

The present research shows a tendency to DC systems due to the several advantages they report. In fact, the presence of HVDC installations all over the world is permanently increasing (Fig. 4) and several projects about DC distribution lines in buildings can be found (Table 7). For the particular case of microgrids, it has been shown that although the number of DC microgrids has been growing during the last years (Fig. 11(b)), still most of them use AC distribution lines (Tables 16 and 17). This is because DC microgris need more research efforts in standardization, bus selection and islanding control techniques are needed. Thus, before DC microgrids are settled, hybrid AC/DC microgrids could be the intermediate step.

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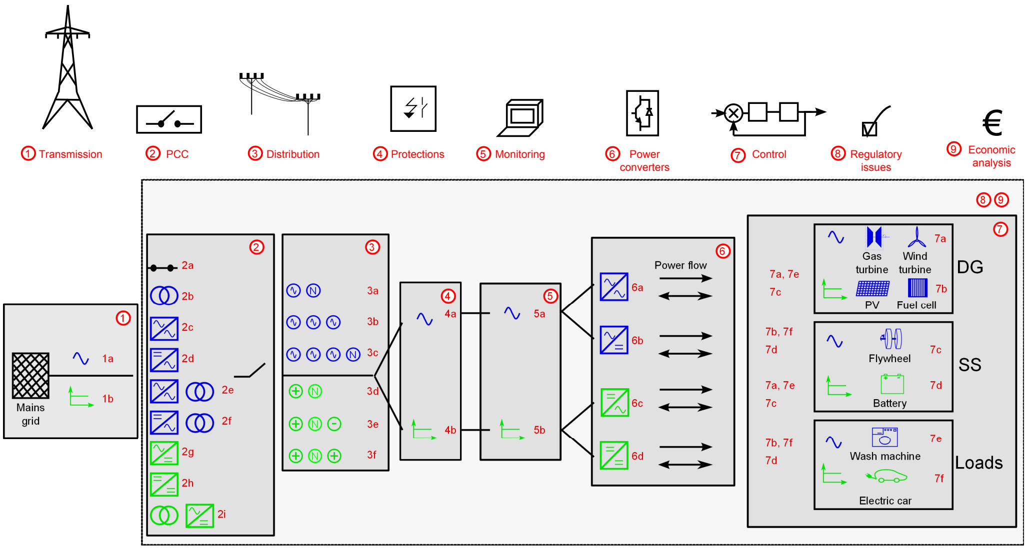


Figure 2: A general scheme of a microgrid. Elements that differ in AC microgrids (blue) and elements that differ in DC microgrids (green).

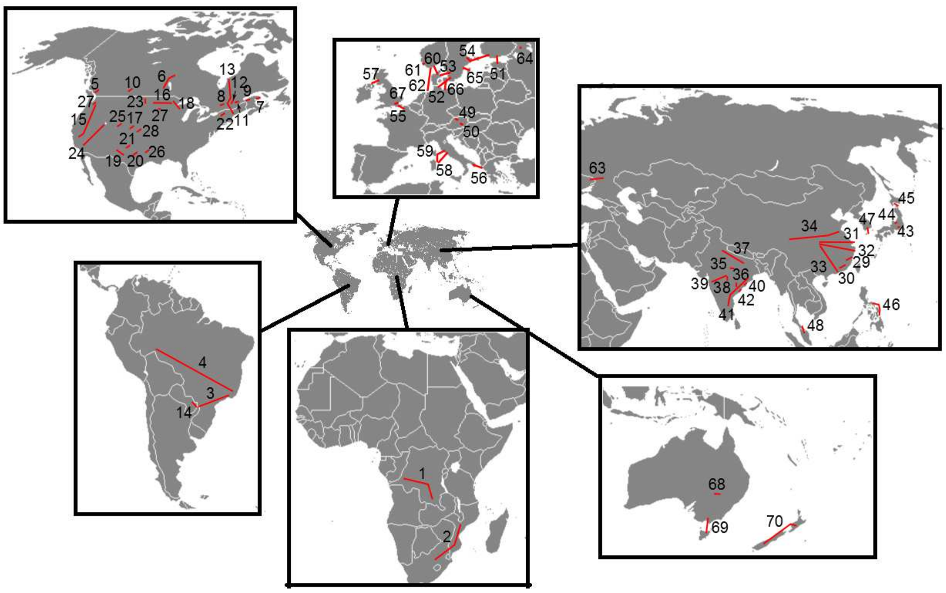


Figure 3: Principle HVDC installations all over the world. *Note: numbers referred to Table 3.*

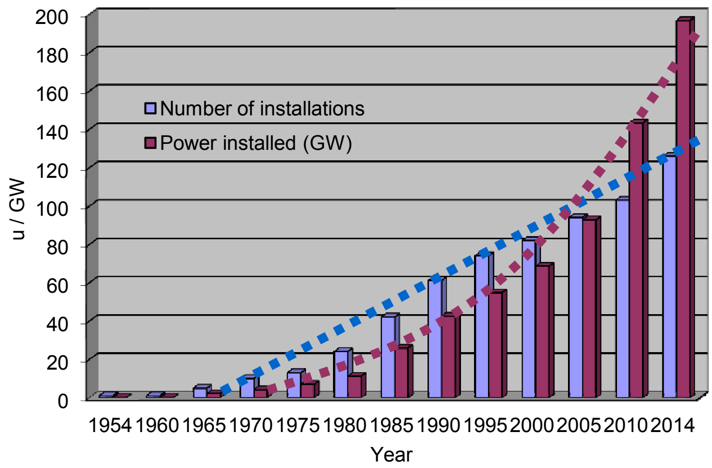


Figure 4: Evolution of the number and power of HVDC installations installed all around the world.

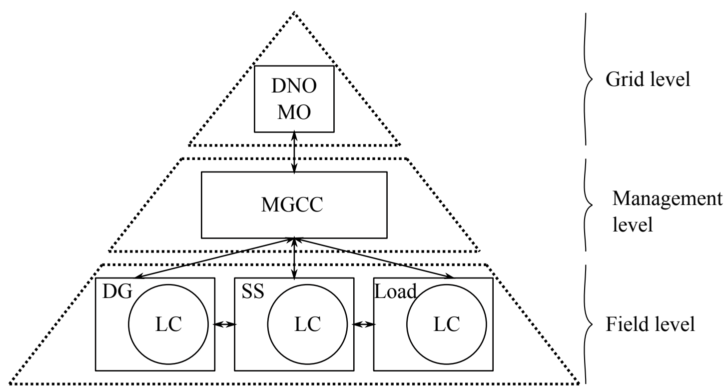


Figure 5: General architecture of centralised and decentralised controls of microgrids.

Table 18: Main power converters topologies for photovoltaic panels and wind turbines.

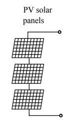
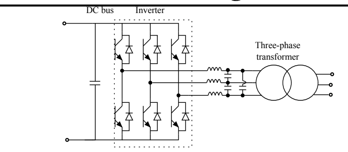
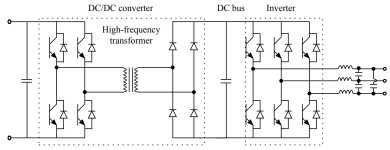
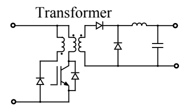
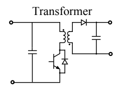
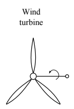
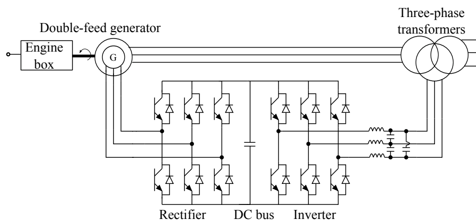
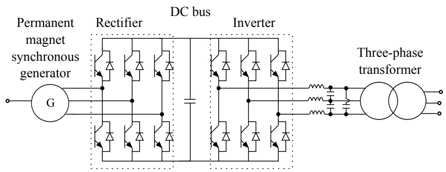
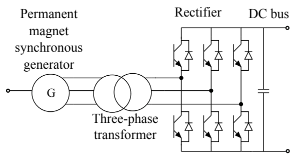
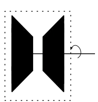
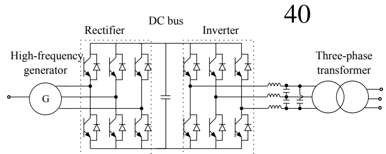
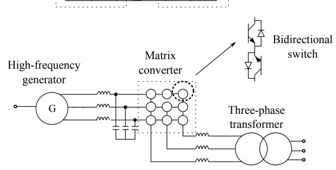
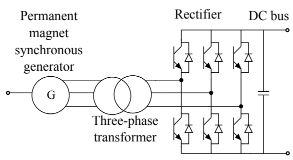
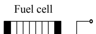
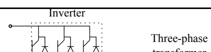
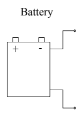
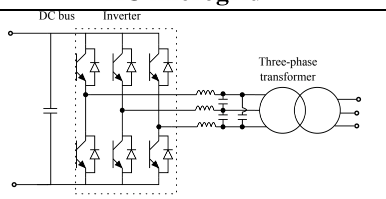
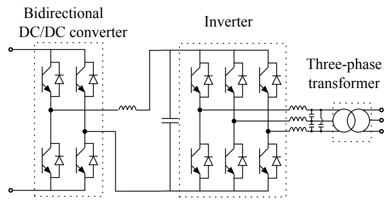
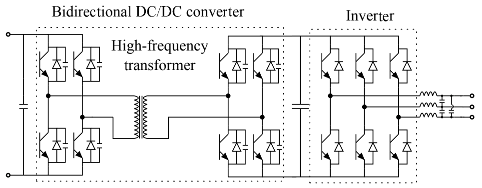
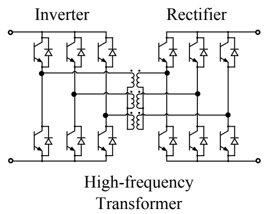
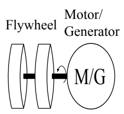
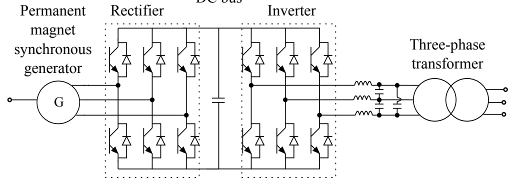
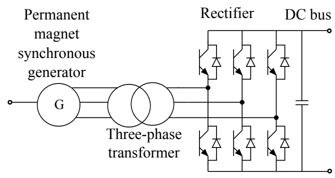
Generator	AC microgrid	DC microgrid
	 	 
	 	
Microturbine 	 	
Fuel cell 		Transformer

Table 19: Main power converters topologies for batteries and flywheels.

Storage System	AC microgrid	DC microgrid
	  	
		

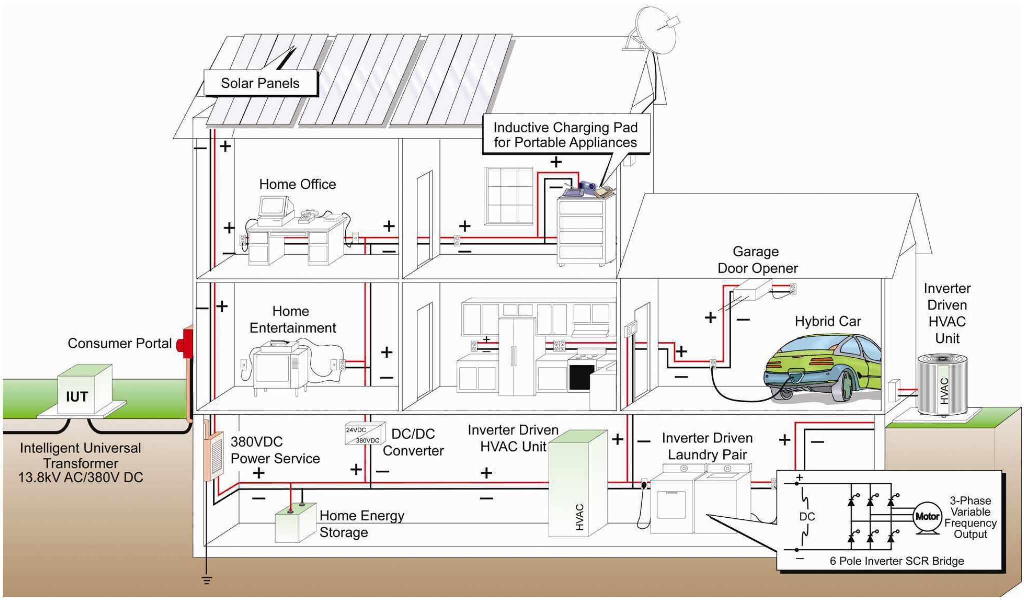


Figure 6: DC-Powered home example proposed in IEC SG4. *Courtesy of Electric Power Research Institute (EPRI)*.

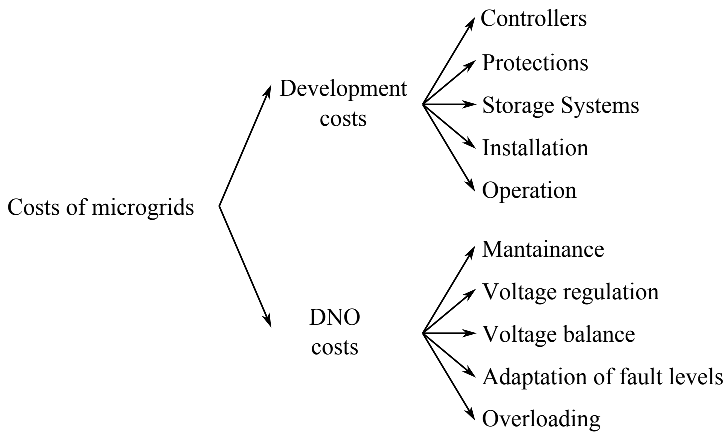


Figure 7: Classification of the costs related to microgrids.

Figure 8: Sendai microgrid in Fukushima, Japan. *Courtesy of New Energy and Industrial Technology Development Organization (NEDO)*.

Figure 9: Antarctic Princess Elisabeth Researh Station is electrically feeded by means of an islanded microgrid based on renewable energies. *Courtesy of Antarctic Princess Elisabeth Researh Station*.

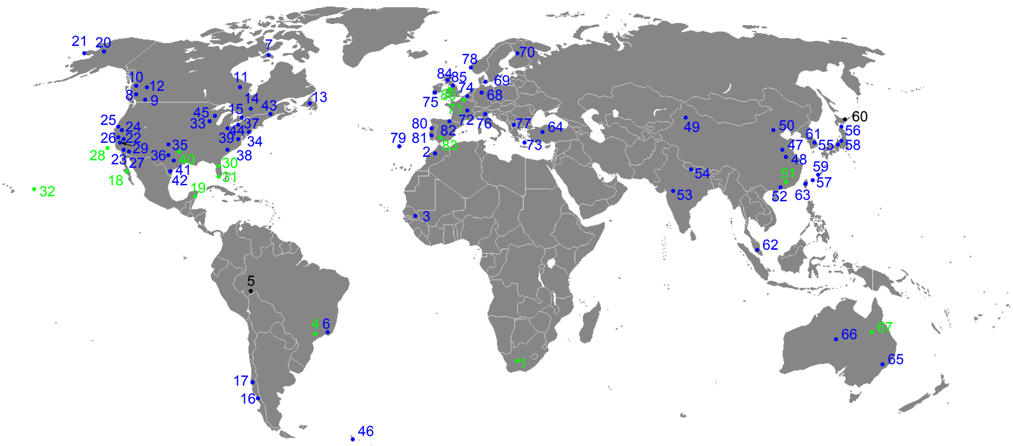
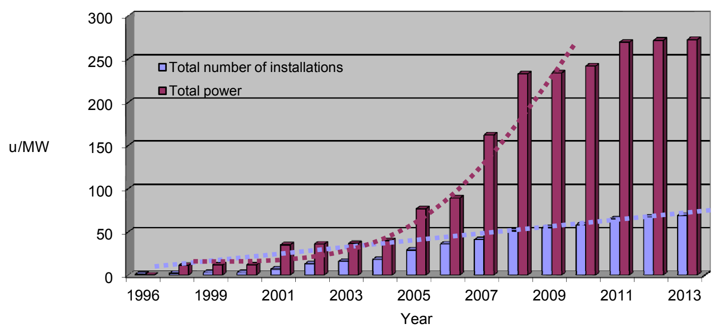
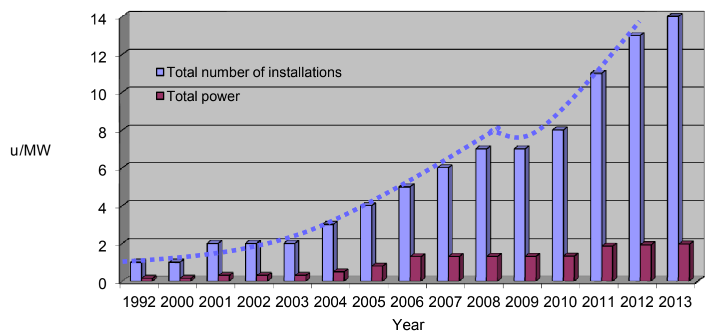


Figure 10: AC (blue), DC (green) and hybrid AC/DC (black) microgrids all around the world.



(a) AC microgrids.



(b) DC microgrids.

Figure 11: Quantity and total power installed in AC and DC microgrids.