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Analysis of Electrical Microgrids and Associated Technologies

J.I. San Martin[1], F.J. Asensio[1], I. Zamora[2], G. Saldaña[1], O. Oñederra[2], I.J. Oleagordía[2]
Department of Electrical Engineering - University of the Basque Country (UPV/EHU)

[1] Engineering School of Gipuzkoa,
Avda. Otaola, 29, 20600 Eibar (Spain)
e_mail: joseignacio.sanmartin@ehu.eus

[2] Engineering School of Bilbao
Alda. Urquijo s/n, 48013 Bilbao (Spain)
e_mail: inmaculada.zamora@ehu.eus

Abstract. This paper focuses on the most relevant aspects on the energy generation and storage technologies integration into electrical microgrids (MGs) structures. In this sense, the most important characteristics associated with electric generation resources proposed for this type of grids are reviewed. Additionally, energy storage technologies are analysed for the most appropriate integration into MGs. Finally, the manuscript reviews the most outstanding MGs developed around the world that include the integration of the most advanced generation and storage technologies.

Key words

Distributed Generation, Microgrids, Generation technologies, Storage Technologies, Distributed Technologies applications.

1. Introduction

Currently, there is a trend towards decentralization, decarbonisation and democratization of the electrical systems [1]. This trend, also known as the "three D's", seeks to replace obsolete infrastructures, to improve the reliability and quality of electricity supply, to provide energy to remote areas of difficult access and to reduce harmful emissions. In this sense, microgrids (MG) behave like architectures of electrical networks that allow access to electrical and thermal energy to broad sectors of the population, from residential areas of cities to rural areas of difficult access.

The concept of MG as a distributed small-scale generation in DC was introduced by Thomas Edison at the end of the 19th century. The growing demand caused the centralization and consolidation of large generating units and long power transport lines [2]. From the 1920s to the 1970s, centralized generation was promoted based on the ability to extract energy from generation resources which were far from the consumption location, thus promoting the development of the current power grid [3,4]. However, environmental concerns, Distributed Energy Resource (DER) technologies, and the economic risks inherent in the construction of massive generation facilities and transmission infrastructures are causing electric utilities to gradually transform from large and centralized to small and decentralized infrastructures over time. A network architecture that is able to manage the power generation and to supply subsections of the network that could be automatically isolated from a larger network is one of solutions that is being promoted. This way, subsections could provide critical services even when the main network fails. This approach was called "Microgrid" [2,4].

A MG is a small-scale power grid that consists of distributed generation (DG) units, energy storage systems (ESS), and electrical and thermal loads that operate as a single control unit at the distribution voltage level. The MGs can operate connected to the main grid or in an isolated way [5-9]. In general, under normal operation, the MG will work connected to the network, but in case of any disturbance occurs in the main network, the MG will disconnect quickly from it and will continue operating in island mode [10].

MGs must have their own control to guarantee the correct operation and coordination of the different DERs. In general, a Microgrid Central Controller (MGCC) is needed to manage the operation within the MG, the energy flows and the interconnection with the main network. In addition, all devices of the MG need to communicate with the MGCC. Traditionally, this control is carried out through a three-level hierarchical scheme [11,12]: Distribution Management System (DMS) or tertiary control, Microgrid Central Controller (MGGC) or secondary control and Load Control (LC) or primary control [13,14,15,16]. Fig. 1 shows a typical example of an electrical MG in which the DMS, MGGC and LCs can be shown.

The primary control operates in the time range from milliseconds to minutes and reacts to the transient dynamics of the DERs and the system, responding to any instantaneous deviation in the voltage or frequency of the system.

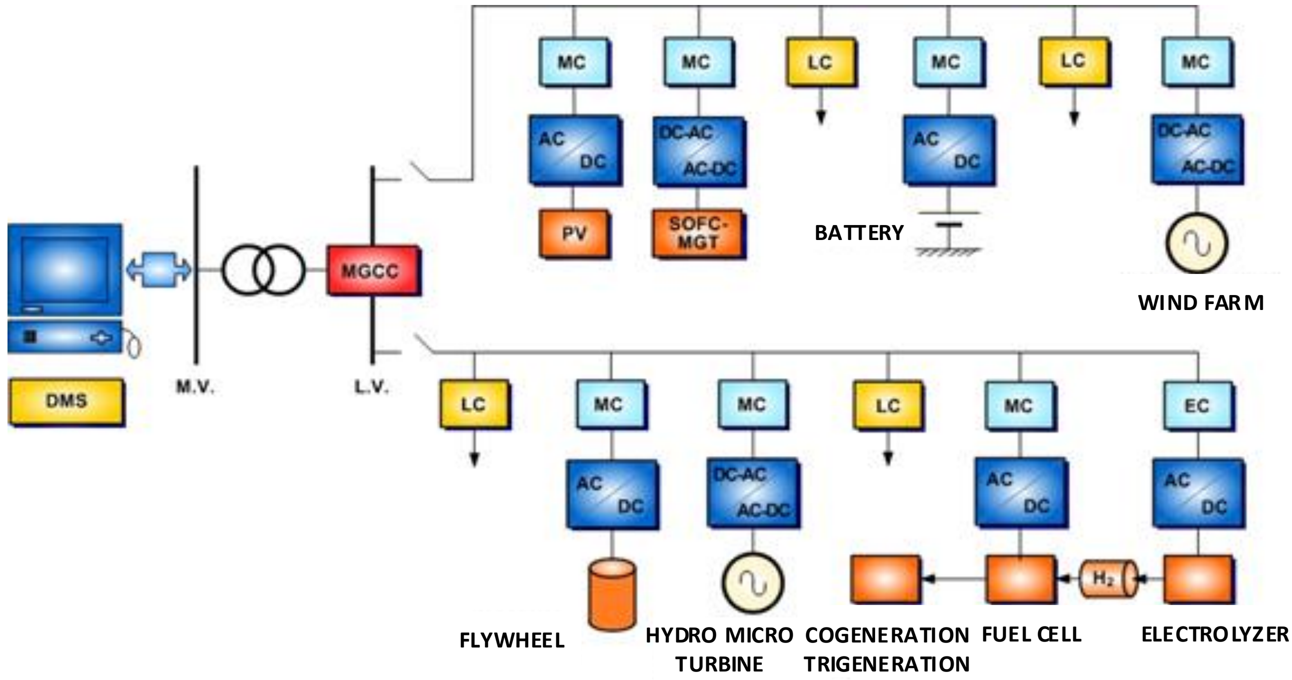

Fig. 1: Example of an electrical microgrid.

This primary controller acts as a local control for each DER unit and uses local measurements and responds to short-term events, such as an island detection, sudden misalignments of active and / or reactive energy, and shared power. The secondary control operates in the time range from minutes to hours, and includes the discrete dispatch of DERs. This level is controlled by the MGCC. This controller is responsible for optimally coordinating and operating all the components connected in the same MG, ensuring the general maintenance of the grid parameters in both connected mode and island mode. The secondary control also incorporates strategies and operation controls such as intentional island operation, resynchronization and load-shedding. The tertiary control operates in the time range from hours to days and involves communication with the different MGCCs and the administration of the MG when it operates in the market. The main entities at this level are the distribution network operator (DNO) and the market operator (MO) who are delegates of the main network.

The MGs can be designed to operate in AC or DC. Each alternative has different characteristics, implying different advantages and drawbacks that must be assessed. The comparisons between the two types of MGs in terms of control, protections and power losses are analysed in [17-20]. In these publications, the advantages and disadvantages of each technology are analysed, identifying and classifying the configurations and feasible architectures required to implement a MG. The aforementioned objectives become a tool that allows choosing the most suitable MG that meets the specifications required in a given situation. In addition, this analysis constitutes an image of the state of the art of MGs, and also proposes research lines to address the current needs of the MGs and the further development of them.

2. Generation technologies associated with electrical microgrids

MGs are systems that integrate the resources of distributed generation to supply a variable number of distributed loads. Regarding distributed generators, they can be based on renewable or non-renewable resources. This characteristic allows to adequately exploit the available renewable resources in each location: water, wind, sun, biomass, etc.

Tables 1 and 2 indicate the most relevant properties of generation technologies that use renewable and non-renewable resources [21]. These tables show that the systems based on wind energy and small hydroelectricity offer the highest efficiency among technologies based on renewable energies. Although ocean energy is a very promising source of energy, it still requires further research and development to be profitable and to reach the market with guarantees of success.

3. Storage technologies associated with electrical microgrids

The use of storage technologies improves the stability of the network, the quality and reliability of the power supply and the overall efficiency of a MG [22, 23]. In Tables 3 and 4, the energy storage technologies available for most relevant MG applications are exposed [24, 25, 26]. It is interesting to note that the Superconducting Magnetic Energy Storage (SMES) provides high efficiency. However, this technology is still in the demonstration stage.

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
Internal combustion engine	Diesel or gas	AC	3-6,000	30-43	~80-85	✓ Low cost ✓ High efficiency ✓ Ability to use various inputs	× Environmentally unfriendly emissions
Gas turbine	Diesel or gas	AC	0.5-30,000	21-40	~80-90	✓ High efficiencies when using CHP ✓ Environmentally friendly ✓ Cost effective	× Too big for small consumers
Micro-turbine	Bio-gas, propane or natural gas	AC	30-1,000	14-30	~80-85	✓ Small size and light weight ✓ Easy start-up and shut-down ✓ Low maintenance costs	× Expensive technology × Cost-effectiveness sensitive to the fuel price × Environmentally unfriendly emissions
Fuel cell	Ethanol, H_2, N_2, natural gas, PEM, DC phosphoric acid or propane	DC	1-20,000	5-55	~80-90	✓ One of the most environmentally friendly generators ✓ Extremely quiet ✓ Useful for CHP 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	Disadvantages
Wind	Wind	AC	0.2-3,000	- a	~50-80	✓ Day and night generation ✓ One of the most developed renewable energy technologies	× Still expensive × Storage mechanisms required
Photovoltaic systems	Sun	DC	0.02-1,000	- a	~40-45	✓ Emission free ✓ Useful in a variety of applications	× Storage mechanisms required
Biomass gasification	Biomass	AC	100-20,000	15-25	~60-75	✓ Minimal environmental impact ✓ Available throughout the world ✓ Alcohol 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	5-100,000	- a	~90-98	✓ Economic and environmentally friendly ✓ Relatively low up-front investment costs and maintenance ✓ Useful for providing peak power and spinning	× Suitable site characteristics required × Difficult energy expansion × Environmental impact
Geothermal	Hot water	AC	5000-100,000	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	10-1,000	- a	- a	✓ High power density ✓ More predictable than solar or wind	× Lack of commercial projects × Unknown operations and maintenance costs
Solar thermal	Sun and power	AC	1,000-80,000	30-40	~50-75	✓ Simple, low maintenance ✓ Operating costs nearly zero ✓ Mature technology	× Unknown operations and maintenance costs × Low energy density × Limited scalability

a: No data available.

Table 3: Comparison of technical characteristics of EES systems.

Systems	Power rating and discharge time		Storage duration		Capital cost		
	Power rating	Discharge time	Self-discharge per day	Suitable storage duration	$/kW	$/kWh	c$/kWh-Per cycle
PHS	100-5,000 MW	1-24 h+	Very small	Hours-months	600-2,000	5-100	0.1-1.4
CAES	5-300 MW	1-24 h+	Small	Hours-months	400-800	2-50	2-4
Lead-acid	0-20 MW	Second-hours	0.1-0.3%	Minutes-days	300-600	200-400	20-100
NiCd	0-40 MW	Second-hours	0.2-0.6%	Minutes-days	500-1,500	800-1,500	20-100
NaS	50 kW-8 MW	Second-hours	~20%	Seconds-hours	1,000-3,000	300-500	8-20
ZEBRA	0-300 kW	Second-hours	~15%	Seconds-hours	150-300	100-200	5-10
Li-ion	0-100 kW	Second-hours	0.1-0.3%	Minutes-days	1,200-4,000	600-2,500	15-100
Fuel cells	0-50 MW	Seconds-24 h+	Almost zero	Hours-months	10,000+		6,000-20,000
Metal-Air	0-10 kW	Seconds-24 h+	Very small	Hours-months	100-250	10-60	
VRB	30 kW-3 MW	Seconds-10 h	Small	Hours-months	600-1,500	150-1,000	5-80
ZnBr	50 kW-2 MW	Seconds-10 h	Small	Hours-months	700-2,500	150-1,000	5-80
PSB	1-15 MW	Seconds-10 h	Small	Hours-months	700-2,500	150-1,000	5-80
Solar fuel	0-10 MW	1-24h+	Almost zero	Hours-months	-	-	-
SMES	100 kW-10 MW	Miliseconds-8 h	10-15%	Minutes-hours	200-300	1,000-10,000	
Flywheel	0-250 kW	Miliseconds-15 min	100%	Seconds-minutes	250-350	1000-5000	3-25
Capacitor	0-50 kW	Miliseconds-60 min	40%	Seconds-hours	200-400	500-1,000	
Super-capacitor	0-300 kW	Miliseconds-60 min	20-40%	Seconds-hours	100-300	300-2,000	2-20
Al-TES	0-5 MW	1-8 h	0.5%	Minutes-days		20-50	
CES	100 kW-300 MW	1-8 h	0.5-1.0%	Minutes-days	200-300	3-30	2-4
HT-TES	0-60 MW	1-24h+	0.05-1.0%	Minutes-months		30-60	

Table 4: Comparison of technical characteristics of EES systems

Systems	Energy and power density				Life time and cycle life		Influence on environment	
	Wh/kg	W/kg	Wh/L	W/L	Life time (years)	Cycle life (cycles)	Influence	Description
PHS	0.5-1.5		0.5-1.5		40-60		Negative	Destruction of trees and green land for building the reservoirs
CAES	30-60		3-6	0.5-2.0	20-0		Negative	Emissions from combustion of natural gas
Lead-acid	30-50	75-300	50-80	10-400	5-15	500-1,000	Negative	Toxic remains
NiCd	50-75	150-300	60-150		10-20	2,000-2,500		
NaS	150-240	150-230	150-250		10-15	2,500		
ZEBRA	100-120	150-200	150-180	220-300	10-14	2,500+		
Li-ion	75-200	150-315	200-500		5-15	1,000-10,000+		
Fuel cells	800-10,000	500+	500-3,000	500+	5-15	1,000+	Negative	Remains and/or combustion of fossil fuel
Metal-Air	150-3,000		500-10,000			100-300	Small	Little amount of remains
VRB	10-30		16-33		5-10	12,000+	Negative	Toxic remains
ZnBr	30-50		30-60		5-10	2,000+		
PSB	-	-	-	-	10-15			
Solar fuel	800-100,000		500-10,000		-	-	Benign	Usage and storage of solar energy
SMES	0.5-5	500-2,000	0.2-2.5	1,000-4,000	20+	100,000+	Negative	Strong magnetic fields
Flywheel	10-30	400-1,500	20-80	1,000-2,000	~15	20,000+	Almost none	
Capacitor	0.05-5	100,000+	2-10	100,000+	~5	50,000+	Small	Little amount of remains
Super-capacitor	2.5-15	500-5,000		100,000+	20+	100,000+	Small	Little amount of remains
Al-TES	80-120		80-120		10-20		Small	
CES	150-250	10-30	120-200		20-40		Positive	Removing contaminates during air liquefaction (Charge)
HT-TES	80-200		120-500		5-15		Small	

Table 3 also shows that there are other technologies such as Pumping Hydraulic Storage (PHS) or Compressed Air Energy Storage Systems (CAES) that, despite their lower efficiencies, have higher capacities with longer lifetimes. The connection schemes of the most used storage technologies can be found in [27]. These technologies must ensure a secure energy supply and must help achieving better energy quality in MGs.

4. Microgrids currently operating worldwide

In this section, structures of electric MGs that have been developed worldwide are exposed, highlighting the most important properties of them. In this sense, several installations of electrical MGs deployed worldwide have been considered to analyse their results. Tables 5, 6, 7 and 8 summarize the experiences in MGs classified according to their location, resources, storage technologies, controls, loads, etc. [15]. Some organizations are carrying out studies on MGs, such as the Consortium for Electric Reliability Technology Solutions (CERTS) in the USA. The Consortium for Electric Reliability Technology Solutions (NEDO) in Japan, and MICROGRIDS and MORE MICROGRIDS in Europe. Most of the MGs implemented have at least one of the following purposes:

1) Give access to electricity to remote areas, where it is difficult to connect to the main grid. Some examples could be: the micro-networks in Africa (Akkan, Diakha Medina, Lucingweni [28, 29, 30] and remote communities that operate in islanded mode (farm in Kozuf, Macedonia [31]). Furthermore, islanded mode lets the islands to be autonomous when accessing to electricity.

2) Development of studies: many projects use their own micro-networks to study control schemes, communication protocols, P / f and Q / V controls, such as the MORE MICROGRIDS project [31] or the DISPOWER project [32]. In addition, many universities [15] stand out, such as Manchester, Leuven, Santa Clara, San Diego [33], Howard, Hefei University, and Technological Institutes, such as the Illinois Institute of Technology [34], which has developed its own micro-network to carry out experiments being also self-producers.

3) Improve security in case of wars or disasters: 40 military bases in the USA are operating as MGs and the Department of Defense is researching the deployment of small MGs in problematic areas [148]. This interest in MGs has grown in the USA after hurricanes like Katrina and Sandy, which caused long periods without energy.

Table 5: Examples of microgrids in Europe.

Situation		Project manager	Type		Control		Structure	
Place	Country		Real	Test-bed	Cent.	Decent.	AC	DC
Bornholm island	Denmark	More microgrids project	✓		a		✓	
Lyon	France	NEDO		✓	a		✓	
Kassel	Germany	The Institut für Solare Energieversorgungstechnik (ISET), University of Kassel Institute for Electrical Energy Technology (IEE)		✓	✓		✓	
Manheim Wallstadt	Germany	More microgrids project	✓			✓		
Stutensee	Germany	DISPOWER project	✓		✓		✓	
Atenas	Greece	National Tchnical University of Athens (NTUA)		✓		✓	✓	
Milan	Italy	Ricerca Sistema Energetico (RSE)		✓	✓			✓
Agria pig farm	Macedonia	More microgrids project	✓		a		✓	
Bronsbergen	Netherlands	More microgrids project	✓		✓		✓	
Groningen	Netherlands	KEMA	✓			✓	✓	
Utsira	Norway	StatoilHydro and Enercon	✓		✓		✓	
Ilhavo	Portugal	More microgrids project	✓		✓		✓	
Barcelona	Spain	Institut de Recerca en Energia de Catalunya (IREC)		✓	a		✓	
Derio	Spain	More microgrids project		✓	✓	✓	✓	
Miñano	Spain	Ikerlan		✓	✓		✓	
Horizon, Manchester	UK	H2Ope	✓		a		a	
Manchester	UK	University of Manchester	✓		✓		✓	

a: No data found.

Table 6: Examples of microgrids in Asia and Oceania.

Situation		Project manager	Type		Control		Structure	
Place	Country		Real	Test-bed	Cent.	Decent.	AC	DC
Newcastle	Australia	CSIRO Energy Center		✓	✓		✓	
Hefei	China	Hefei University of Technology (HFUT)		✓		✓		
Tianjin	China	Tianjin University		✓	✓		✓	
Changwon	Korea	Korea Electrotechnology Research Institute (KERI)		✓	✓		✓	
Uttar Pradesh	India	Mera Gao Power (MGP)		✓	✓		✓	
Aichi	Japan	Aichi Institute of Technology (AIT), NEDO	✓					
Akagi	Japan	NEDO	✓	✓		✓		
Hachinoche	Japan	NEDO	✓		✓		✓	
Kyoto Eco-Energy	Japan	NEDO		✓	✓		✓	
Sendai	Japan	NEDO	✓		✓	✓		

Table 7: Examples of microgrids in North America.

Situation		Project manager	Type		Control		Structure	
Place	Country		Real	Test-bed	Cent.	Decent.	AC	DC
Boston Bar	Canada	BC Hydro	✓			✓	✓	
Senneterre	Canada	Hydro Quebec (HQ)	✓				✓	
Albuquerque, New Mexico	USA	NEDO, Sandia National Laboratories, The University of New Mexico and Japanese companies		✓	a		a	

Ansonia, Connecticut	USA	Pareto Energy, Ltd. And Connecticut Center for Advanced Technology (CCAT)	✓		a		a	
Borrego Springs, California	USA	San Diego Gas & Electric Company (SDG & E)	✓		✓		✓	
Columbus	USA	Dolan Technology Center		✓			✓	
Washington	USA	Howard University		✓	a		a	
Chicago	USA	Illinois Institute of Technology		✓			a	
Los Alamos, New Mexico	USA	NEDO		✓	a		a	
Madison	USA	University of Wisconsin		✓			✓	
Marin County, California	USA	Xanthus Consulting International, Infotility, Inc.	✓				✓	
California	USA	Santa Clara University		✓	a		✓	
Stamford, Connecticut	USA	Pareto Energy	✓		a		a	
San Diego	USA	University California San Diego		✓	a		a	
Twenty-nine palms, California	USA	General Electric (GE)	✓		✓		✓	

a: No data found.

Table 8: Examples of islanded microgrids all around the world.

Situation			**Project manager**	**Control**		**Structure**	
Region	**Place**	**Country**		**Cent.**	**Decent.**	**AC**	**DC**
Africa	Akkan	Morocco	2	✓		✓	
	Diaka Madina	Senegal	2	✓		✓	
	Lucingweni	South Africa	National Energy Regulator of South Africa (NERSA)		✓	✓	✓
Antartic	Princess Elisabeth Station	Antartic	Laborelec	✓		✓	
Asia	Kuroshima island	Japan	Kyushu Electric Power	✓		✓	
	Miyako island, Okinawa	Japan	Okinawa Electric Power Company (OEPC)	a		✓	
	Town Island	Hong Kong	Hong Kong University (HKU)	✓		✓	
Europe	Kythnos	Greece		✓		✓	
North America	Bella Cola	Canada	BC Hydro, GE, PowerTech	✓		✓	
	Hartley Bay	Canada	Pulse Energy (ICE)		✓	✓	
	Kasabonika Lake	Canada	Hydro One, GE, University of Waterloo	✓		✓	
	Nemiah Valley	Canada	NRCan	✓		✓	
	Ramea Island	Canada	N & L Hydro, Nalcor Energy, NRCan, Frontier Power	✓		✓	
	Colonias, Texas	USA	Texas State Energy Conservation Office (SECO), Texas Engineering Experiment Station, Xtreme Power	✓		✓	
	Fort Bragg, North Caroline	USA	Encorp, Honeywell	✓		✓	
Oceania	Kings Canyon	Australia	UNSW (Sydney)	✓		✓	
South America	Chico Mendes	Brazil	Electrobas	✓		✓	✓
	Ilha da Ferradura	Brazil	a	✓		✓	

a: No data found.

5. Conclusion

This paper contributes to the definition of the electrical MGs usage in power systems. In this sense, MGs provide an adequate structure in terms of performance of a distributed energy generation system. The MGCC links, controls and manages smartly this type of generation systems.

A review of most relevant properties in energy generation and storage technologies in the development of electric MGs has been addressed. In this sense, installed capacity, response time, power range, operating modes, efficiencies, electronic devices associated to its integration, etc. are analysed.

Furthermore, major drawbacks for the integration of MGs in power system are exposed. Additionally, technical characteristics of several MGs currently being analysed are specified, among further research proposals from public and private institutions worldwide.

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