Optimal Operation of Hybrid AC/DC Microgrids under Uncertainty of Renewable Energy Resources: A Comprehensive Review

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Abstract

The hybrid AC/DC microgrids have become considerably popular as they are reliable, accessible and robust. They are utilized for solving environmental, economic, operational and power-related political issues. Having this increased necessity taken into consideration, this paper performs a comprehensive review of the fundamentals of hybrid AC/DC microgrids and describes their components. Mathematical models and valid comparisons among different renewable energy sources' generations are discussed. Subsequently, various operational zones, control and optimization methods, power flow calculations in the presence of uncertainties related to renewable energy resources are reviewed.

Keywords: Hybrid AC/DC microgrids; uncertainty modeling; renewable energy sources; optimization.

Nomenclature:

A	*Turbine swept area*	(m^2)	E_{PV}	*PV output Energy*	*(kWh)*
A_{PV}	*Total solar panel area*	(m^2)	$Emission_{Bat}^{t}$	*The total emission of the batteries at hour "t"*	$(kg.MW^{1})$
AA	*Exponential voltage of the battery*	*(V)*	$Emission_{FC}^{t}$	*The total emission of the fuel cell at hour "t"*	$(kg.MW^{1})$
ARB	*Annual rate of benefit*	*($/year)*	$Emission_{Grid}^{t}$	*The total emission of the grid at hour "t"*	$(kg.MW^{1})$
B	*Exponential capacity of the battery*	$(Ah)^{-1}$	$Emission_{MT}^{t}$	*The total emission of the micro turbine at hour "t"*	$(kg.MW^{1})$
B_{Err}	*Difference of calculated and actual battery energy*	*(kWh)*	$Emission_{PV}^{t}$	*The total emission of the photovoltaics at hour "t"*	$(kg.MW^{1})$
c_1 *to* c_5	*Coefficients modelling* c_p	-	$Emission_{WT}^{t}$	*The total emission of the wind turbine at hour "t"*	$(kg.MW^{1})$
C_{Bat}	*Battery incremental cost*	*($/kWh)*	$Exp(s)$	*Representing the exponential zone dynamics of the battery*	*(V)*
C_{FC}	*Fuel cell incremental cost*	*($/kWh)*	H_{PV}	*Annual average solar radiation on tilted panels*	(kWh/m^2)
C_{Grid}	*Grid incremental cost*	*($/kWh)*	i^{*}	*Representing the frequency current dynamics*	*(A)*
C_{MT}	*Microturbine incremental cost*	*($/kWh)*	i_{bat}	*Battery current*	*(A)*
c_p	*Performance coefficient of the wind turbine*	-	I_d	*Armature current*	*(A)*
C_{PV}	*PV incremental cost*	*($/kWh)*	it	*Extracted Capacity of the battery*	*(Ah)*
C_{WT}	*Wind turbine's incremental cost*	*($/kWh)*	k_p	*Proportional gain of PI controller*	-
Cap	*Capacity*	*(kW)*	k_I	*Integral gain of PI controller*	-
CC	*Capital cost*	*($/kW)*	k_m	*Motor wiring constant*	-
CC_{Bat}	*Battery capital cost*	*($)*	k_p	*Power gain*	-
$Cost_{Bat}$	*The total cost of battery operation*	*($)*	K	*Polarization resistance*	(Ω)
$Cost_{FC}$	*The total cost of fuel cell operation*	*($)*	L_H	*Inductor value at high side*	*(H)*
$Cost_{Grid}$	*The total cost of grid operation*	*($)*	LF	*Load factor*	-
$Cost_{MT}$	*The total cost of microturbine operation*	*($)*	LT	*Lifetime*	*(year)*
$Cost_{PV}$	*The total cost of PV operation*	*($)*	m	*Number of discharging cycles*	-
$Cost_{WT}$	*The total cost of wind turbine operation*	*($)*	$N_{WT\,/\,MT\,/\,FC\,/\,PV}$	*Number of units*	-
DC^{t}	*Discharge capacity at hour "t"*	*(Ah)*	OM	*Operation and maintenance cost*	*($/kWh)*
E_0	*Constant voltage of the battery model*	*(V)*	p, K	*Battery coefficients*	-
E_B	*Battery energy*	*(kWh)*	P_g	*Generation of power units*	*(kW)*
E_{Bat}^{t}	*Battery energy at hour "t"*	*(kWh)*	P_{Bat}^{t}	*The Battery's production at hour "t"*	*(kW)*
$E_{Bat}^{initial}$	*Battery initial energy at hour "t"*	*(kWh)*	$P_{Bat_{\min}}^{t}, P_{Bat_{\max}}^{t}$	*Minimum and maximum battery power value at hour "t"*	*(kW)*
$E_{D,v}^{t}$	*Drive energy of the vehicle at hour "t"*	*(kWh)*	$P_{C\_Bat}^{t}$	*Battery charging power at hour "t"*	*(kW)*
$P_{Dch\_Bat}^{t}$	*Battery discharging power at hour "t"*	*(kW)*	S_{LK}	*Complex power*	*(VA)*
P_{FC}^{t}	*The fuel cell's production at hour "t"*	*(kW)*	$sel(s)$	*Battery charging mode*	$\in \{-1,0,1\}$
$P_{FC_{\min}}^{t}, P_{FC_{\max}}^{t}$	*Minimum and maximum grid power value at hour "t"*	*(kW)*	U_{charge}^{t}	*The states of charge of the batteries*	-

P_{Grid}^{t}	*The grid's production at hour "t"*	*(kW)*	$U_{discharge}^{t}$	*The state of the discharge of the batteries*	-
$P_{Grid_{\min}}^{t}, P_{Grid_{\max}}^{t}$	*Minimum and maximum grid power value at hour "t"*	*(kW)*	U_{v}^{t}	*Vehicle's charge/discharge state at hour "t"*	-
P_{l}^{t}	*The load's production at hour "t"*	*(kW)*	U_g	*The on/off state of FC/MT units*	$\in \{0,1\}$
P_m	*Mechanical output power of the WT unit*	*(MW)*	V	*Voltage*	*(V)*
P_{m_pu}	*Per united P_m*	-	V_d	*Motor voltage*	*(V)*
P_{MT}^{t}	*The microturbine's production at hour "t"*	*(kW)*	V_H	*Terminal voltage*	*(V)*
$P_{MT_{\min}}^{t}, P_{MT_{\max}}^{t}$	*Minimum and maximum micro turbine power value at hour "t"*	*(kW)*	V_L	*Voltage at low side*	*(V)*
P_{PV}^{t}	*The photovoltaics' production at hour "t"*	*(kW)*	V_{wind}	*Wind speed*	*($m.s^{-1}$)*
P_{spec}	*Active power*	*(W)*	$\mathbf{X}$	*Decision variable vector*	-
P_{WT}^{t}	*The wind turbine's production at hour "t"*	*(kW)*	β	*Blade pitch angle*	*(deg)*
PR	*Performance ratio of solar panel*	$\in [0.5,0.9]$	η	*Electrical efficiency of the fuel cell*	*(%)*
Q	*Maximum battery capacity*	*(Ah)*	η_c, η_d	*Charge, discharge efficiency*	*(%)*
Q_{spec}	*Reactive power*	*(Var)*	λ	*Tip speed ratio of the rotor blade tip speed to wind speed*	-
R_a	*Armature resistance*	*(Ω)*	λ_b	*The base λ value derived from $c_p - \lambda$ characteristic*	*(rpm)*
RE_{fuel}	*Fuel cost*	*($/kWh)*	ρ	*Air density*	*($kg.m^{-3}$)*
r_{PV}	*Solar panel efficiency*	*(%)*	ω_d	*Armature speed*	*(Rad/s)*

Abbreviations:

Analytical hierarchical process	*AHP*	*Hybrid renewable energy system*	*HRES*	*Renewable energy resources*	*RESs*
Brazil, Russia, India, China & South Africa	*BRICS*	*Imperialist competitive*	*IC*	*Lithium Ion*	*Li-ion*
Backward/ forward sweeping	*BFS*	*Internal combustion engine*	*ICE*	*system average interruption duration index*	*SAIDI*
Constant speed squirrel cage induction generator	*CSSCIG*	*Linear integer programming*	*LIP*	*system average interruption frequency*	*SAIFI*
Concentrated solar power	*CSP*	*Linear-Quadratic Gaussian*	*LQG*	*Semidefinite programming*	*SDP*
Differential evolution	*DE*	*Monte Carlo*	*MC*	*Total harmonic distortion*	*THD*
Doubly fed induction generator	*DFIG*	*Mixed integer linear programming*	*MILP*	*Teaching-learning algorithm*	*TLBO*
Discrete genetic algorithm	*DGA*	*Mixed integer programming*	*MIP*	*Tabu search*	*TS*
Distribution companies	*Dis. Cos*	*Multi-objective genetic algorithm*	*MOGA*	*Unscented transformation*	*UT*
Depth of discharge	*DoD*	*Maximum power point tracking*	*MPPT*	*Vanadium redox*	*VRB*
Energy management system	*EMS*	*microturbine*	*MT*	*Valve regulated lead acid*	*VRLA*
Energy not supplied	*ENS*	*Micro source*	*MS*	*Sodium Sulfur*	*NaS*
Energy storage system	*ESS*	*Optimal power flow*	*OPF*	*Nickel Cadmium*	*NiCd*
Electric vehicle	*EV*	*Point estimate method*	*PEM*	*Nickel Manganese Hybrid*	*NiMH*
Fuel cell	*FC*	*Plug-in electric vehicle*	*PEV*	*Wind turbine*	*WT*
Genetic algorithm	*GA*	*Permanent magnet synchronous machine*	*PMSM*	*Sodium Nickel Chloride*	*ZEBRA*
Generation companies	*Gen. Cos*	*Particle swarm optimization*	*PSO*	*Zinc bromine*	*ZnBr*
Green House Gases	*GHG*	*Photovoltaic*	*PV*		
Grey wolf optimization	*GWO*	*Pulse width modulation*	*PWM*		

1- Introduction

The growing need to utilize renewable energy sources (RESs), the declining fossil fuel resources, the necessity to protect the environment and also the importance of pollution reduction caused by the fossil fuel emissions has led to the inevitable fact of using integrated RESs in current microgrids. From an operational point of view, a hybrid AC/DC microgrid is a gateway, which not only enhances the system performance in the above-mentioned issues, but can also enhance the operational properties of any proposed power system. Nowadays, the renewable energy market is developing faster than ever; therefore, it is expected that the operational considerations will be taken into account in the microgrids, similar to that of power systems. Supporting local energy demands [1] as well as coupling AC and DC loads with their corresponding resources to decrease the regular AC-DC-AC conversion losses [2] is one of the outcomes of utilizing both AC and DC microgrids. Furthermore, increased energy consumption standards in addition to higher reliability and improved power quality and system stability can be achieved by integration of AC and DC microgrids, to form a hybrid AC/DC microgrid [3,4].

About after a century of domination, many of the reasons that led to the choice of a complete AC power system do not exist anymore [5]. Increasing amount of DC loads, development of semiconductors, and high accessibility of RESs in remote and rural areas have made the utilization of DC microgrids possible [6].

Obviously, the distribution of RESs and the different nations' investments in the implementation of the hybrid AC/DC microgrids are not even. In the global status report of the renewables 2018 [7], the top countries' total capacity/ generation to the end of 2017 has been analyzed, as presented in Figure 1. As expected, not only do the energy policies of a country have a direct effect on the level and quality of the produced energy and its variation, but the geographical factors also play a substantial role in this regard. Figure 2. presents the energy production percentage from nonrenewable resources. The higher the RESs penetration, the lower is the dependency on nonrenewables.

In this paper, the above-mentioned issues are analyzed and a comparison of different aspects is provided. In section 2, a definition of hybrid AC/DC microgrids and the reasons that led to their superiority, as well as the benefits and challenges are considered and their various configurations are described. Subsequently, in section 3 different components of microgrids, and their mathematical modelling are analyzed. Section 4, focuses on the environmental, economic and technical viewpoints of hybrid AC/DC microgrids. Different solution methodologies and modeling of uncertainties related to RESs are discussed in sections 5 and 6, respectively. The AC/DC power flow is described in section 7, and finally a conclusion has been provided in section 8.

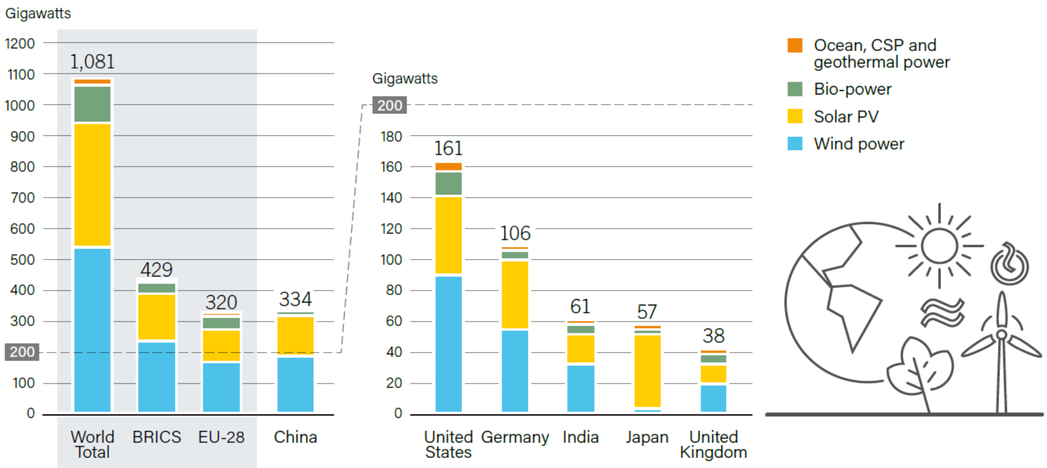

Figure 1. Top countries' total renewable generation to the end of 2017 [7]

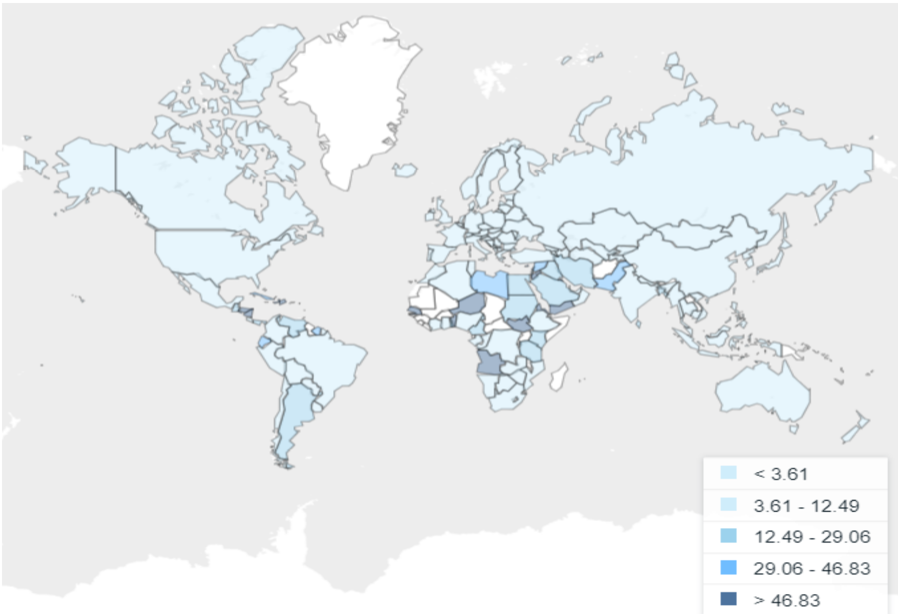

Figure 2. The energy production percentage from nonrenewable resources [7]

2- Hybrid AC/DC Microgrids

As it is known, the first power network was an isolated DC microgrid, mainly consisting of DC power generators. However, due to several reasons such as difficulties in producing the required voltage levels and transmission losses the present power network was formed. Centralized control is the current common operation method of the electrical power network. Pursuant to investment requirements in generation and transmission due to load growth and the lack of governments' supplies to invest in these areas this controlling method has major drawbacks. Moreover, as the efficiency needs to be improved especially in the industrial areas and not all the industries are keeping up with technology improvements the centralized controlling method has lost its popularity. Therefore, in order to reduce the operation and maintenance cost of the current power network with the aforementioned drawbacks, microgrids found their ways back to the power network operation. Several configurations have been proposed for different types of microgrids [8,9]. Considering the general topologies illustrated in Figure 3, microgrids are categorized into three major groups:

- **DC microgrid:** The DC microgrid as we know it today was first developed in the 19th century by Thomas Edison. A DC microgrid mainly consists of DC loads and resources. The advantages of this type of microgrid could be energy storage system integration, higher total efficiency due to less AC-DC-AC conversions and the elimination of distributed generator (DG) synchronization. However, as the generated DC power could not be transferred in long distances, it lost its popularity over time. Nevertheless, the DC microgrid is finding its way back to the energy supply chain as most of the home appliances such as TVs, printers, microwaves, etc. are DC supplied. With advances of PVs and FCs as resources with DC output powers, utilizing DC resources to supply DC loads makes more sense than ever. Research shows that about 30% of the generated AC power is transferred to DC power or at least passes through a converter before being used. Another motivation for reconsideration of DC microgrids is the advances in semiconductor technology. One of the challenges that must be overcome in this microgrid, is the way of integrating the microgrid configuration with the current distribution system.

- **AC microgrid:** This system has dominated the DC system for many years, due to its easy modification of voltage levels with low frequency transformers and facilitated handling of faults and protection. Moreover, the AC power is easy to transfer and most of the industrial appliances need AC power supplement. AC RESs such as WTs, tidal, biogas and wave turbines have been integrated with AC microgrids in recent years. However, the main challenges in AC microgrid control are DG synchronization issues and reactive power control, which might increase the losses of the transmission system. Moreover, since the AC RESs are sensitive to climatic and geographical changes, frequency control of microgrids in which the aforementioned RESs are utilized is a challenging task.

- **Hybrid AC/DC microgrid:** This configuration combines the benefits of AC and DC microgrids and facilitates the integration of AC and DC loads with their corresponding sources. This is a suitable method for utilizing smart grids along with the current network. Voltage transformation, economic feasibility and harmonic control are among other advantages of this configuration. Despite all the mentioned benefits, a hybrid AC/DC microgrid has a few minor drawbacks such as protection issues and complex coordination among the units, which can be solved using optimized operation techniques. Therefore, hybrid AC/DC microgrid is an appropriate case for studying the operational issues and challenges, because of its overall superiority to other types of microgrids.

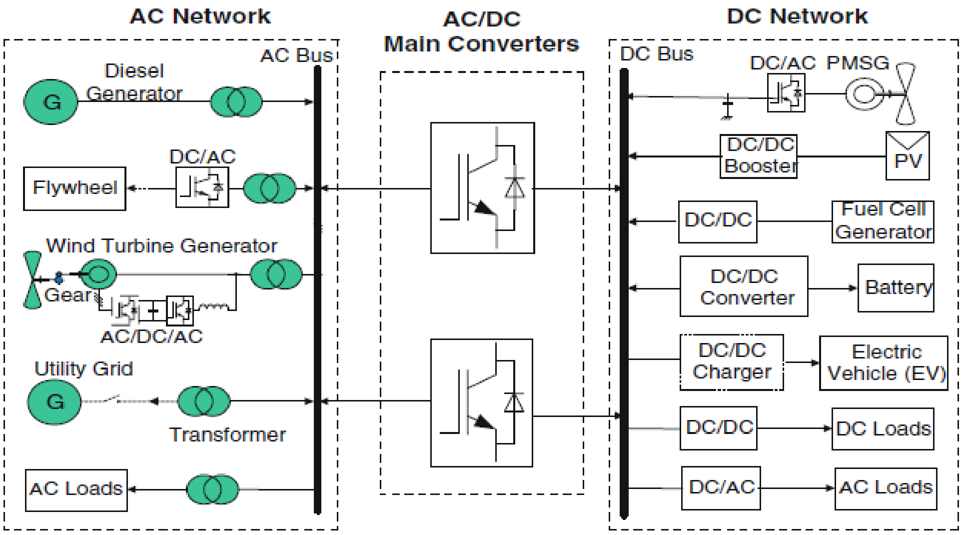

Figure 3. General schematic of a hybrid AC/DC microgrid

There are two main operating modes for a hybrid AC/DC microgrid:

- **Grid-connected mode:** In this mode, the microgrid is connected to the network and all the generating units operate at their maximum operational point. There are two types of grid-connection modes. In the first mode the priority of the grid-connected system is to supply the local needs. In this mode, the surplus generated energy can be injected into the microgrid and any shortages can be supplied by the main grid. In the second grid-connection mode the only responsibility of the grid-connected microgrid is to aggregate generated power and supply it to the main grid. The most important aspect of operating a microgrid in this mode is that the grid plays the role of a large battery for the microgrid. Therefore, it can cover all the seasonal load variations. However, as interfaces are required to connect the microgrid to the main grid the overall cost in this mode is higher. During a fault or according to the operational priorities, the system can also operate in an islanded mode.

- **Islanded mode:** In this mode, connection to the network is cut off and the energy storage system plays a considerable role, which incurs an extra operational cost to the system. Otherwise, the excess energy can't be stored. This mode is more suitable for remote areas and it is mainly used for seasonal purposes, since the local load is the only priority of this operation mode. As PVs are the most cost-effective RESs, they consist the majority of islanded microgrids' capacity. For AC islanded microgrids, not only is the main focus of the converter on the multiple AC-DC-AC conversion, but it also serves as frequency and voltage reference.

3- Hybrid AC/DC Components:

As illustrated in Figure 3, a hybrid AC/DC microgrid consists of the following main parts:

3-1 Load: Generally, the loads that could be fed by a hybrid AC/DC microgrid are categorized into two main groups:

- Thermal loads
- Electrical loads

Normally, a combination of thermal and electrical loads need to be supplied in residential appliances. However, there is no limit to the utilization of hybrid AC/DC microgrids. According to their high integration capabilities, microgrids are also used in commercial, institutional, industrial, rural, remote and military applications. With a total growth of 42.5% of public utilities by 2024, the commercial loads are making up the majority of the microgrid market. Not only do the microgrids play an important backup role for key industries, but they are also utilized for military applications like backing up the marine forces and supplying the required demands on the isolated power system of naval bases [10]. As described in [11] there are mainly two categories of load studies. The first category identifies loads by several measurements and the second one models the load on the basis of the load's constitutional parts. These two categories are also known as static and dynamic modelling. Therefore, the load studies were narrowed down to assume a fixed value for any of the characteristics that could be attributed to a load such as current, impedance and power. Also the loads are modelled based on one of the following categories [12]:

Constant Power (The most common) → $S_{LK} = P_{spsc} + jQ_{Spec}$ (1)

Constant Current → $S_{LK} = |V|(P_{spsc} + jQ_{spsc})$ (2)

Constant Impedance → $|V|^2 (P_{spsc} + jQ_{spsc})$ (3)

In [13-20], the modeling, control, implementation, utilization and sensitivity analysis of a microgrid has been investigated, subject to a constant power load constraint. The constant current [21-23], constant impedance and a combination of constant impedance, current and power, known as a ZIP model [24, 25], have also been analyzed in a few studies as well.

3-2 RESs:

As it has been previously mentioned, the RESs are dominating the microgrid configuration and the market. For this reason, it is necessary to introduce the main components of a hybrid AC/DC microgrid:

3-2-1 Photovoltaic (PV):

The function of a photovoltaic panel is based on the doping of the atoms in the p & n junction layers of the semiconductor that forms the panel exposed to the solar irradiance. There are three main types of photovoltaic cells [26]:

- Monocrystalline
- Polycrystalline
- Amorphous

A detailed review of photovoltaic systems has been performed in [27]. Several commercial photovoltaic cells are available in the market. The characteristics, cost and efficiency of some of these cells are compared in Figure 4.

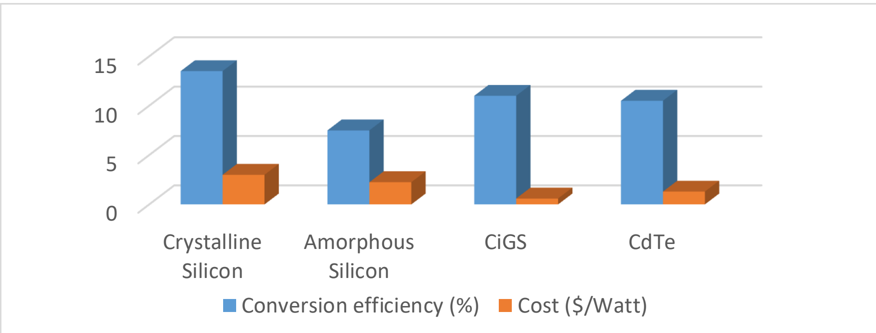

Figure 4. Efficiency and cost comparison of some of the available PV cells in the market

3-2-1-1 Mathematical modelling:

In order to model the effect of the solar cell behavior in different simulations, a physical model is used. According to Figure 5, four main types of PV models can be inferred:

- Ideal model [28]: D1, I_L exist
- Simple model [29]: D1, I_L, R_S exist
- Standard model [30]: D1, I_L, R_S, R_{SH} exist
- Standard model with two diodes [31]: D1, D2, I_L, R_S, R_{SH} exist

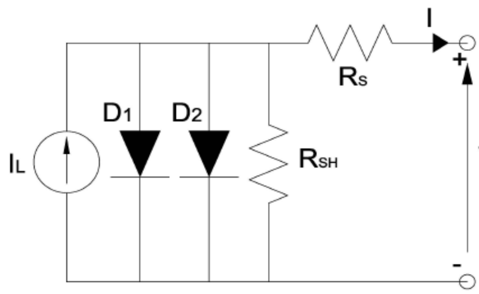

Figure 5. The main schematic of a PV model

The mathematical modelling of the PV array is illustrated in equation (4). The output energy of a PV depends on its area. The efficiency of the panel which is dependent on the material and the PV panel type plays a role in the output energy of the PV. Also, the annual solar radiation and performance ratio must be taken into consideration, whilst calculating PV output energy. Using (4) the output power can be calculated in any required time domain.

$$E_{PV} = A_{PV} \times r_{PV} \times H_{PV} \times PR \tag{4}$$

3-2-1-2 Implementation benefits and challenges:

In order to increase the performance of PV cells, different algorithms have been proposed. In this paper, two major algorithms are compared in Table 1.

Table 1. Comparison of two of most common MPPT tracking methods [26]

No.	Method Description	Advantages	Disadvantages
1	Perturbation & Observation algorithm (P & O) Comparing the power & voltage & their deviation and changing the voltage to gain maximum power	- Simplicity - Popularity	- Inaccurate in case of very high/ very low ΔV, slower than ICM - Doesn't find the global maximum point
2	Incremental Conductance Method (ICM) Comparing voltage and current and changing the voltage to gain maximum power	- Speed - Higher accuracy than P & O - Stability - Less oscillation - Rapid tracking of voltage variations	- Complexity - High cost - Doesn't find the global maximum point

3-2-2 Wind Turbine (WT):

According to the environmental and economic benefits of WTs, they have been considered as one of the reliable substitutions for conventional power resources. The main utilized generator types in wind turbine systems are compared in Table 2 [32].

Table 2. Comparison of wind turbines

No.	Wind Turbine Type	Year	Rated Power	Special Characteristics
1	Constant speed squirrel cage induction generator (CSSCIG) [32]	About 1998	<1.5 MW	Inexpensive, robust, self-starting. Prior to advances in power electronics they were a favorable choice.
2	Doubly fed induction generator (DFIG) [33, 34]	From 1996 to 2000	~1.5 MW	Flexibility, power quality guarantee, relatively inexpensive
3	Brushless Generator [35]	About since 2005	>1.5MW	Variable speed, enhanced fault tolerance
4	Gearless Generator [36]	Since 1991	>1.5MW	Gearbox fault elimination, low-speed 'n' high-torque, expensive and heavy

There are two main control methods for wind turbines, which are illustrated in Table 3[37]:

- **Centralized:** In this method, there is a main center, controlling all the reference values, speeds and currents of the wind farms [38].
- **Decentralized:** In this method every wind turbine acts as an independent unit and possesses its own converter [39].

Table 3. Comparison of two control methods of the wind farms

No.	Method Description	Advantages	Disadvantages
1	Centralized (central power electronic converter) An existing hierarchical controller in two levels i) Local: checking the reference power signals ii) Control: controlling power production	- Separation of the wind turbine and network - Robustness	- Similar average angular speed of all turbines (losing the multi-variable speed mode) - Implementation difficulty
2	Decentralized (individual control)	- Every wind turbine is at its optimum speed	- Coordination and frequency variation issues

There are also several parameters that must be controlled and taken into consideration during the implementation of wind turbines such as voltage and frequency control, active power control, protection, communication, etc. The optimal allocation of wind turbines in distribution networks and in microgrids using metaheuristic algorithms has been analyzed in [40,41].

3-2-2-1 Mathematical modelling:

In case the dynamics of the wind turbines are considered, the modelling will become a tough task. Also dynamic modelling is required to check the system's stability and its ability to be controlled. The general scheme of a wind turbine is shown in Figure 6.

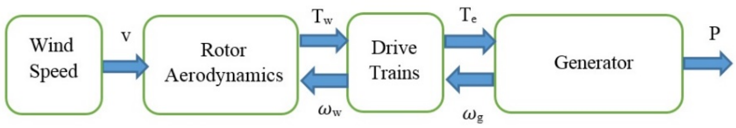

Figure 6. General scheme of a wind turbine

The output power of a WT is a function of the performance coefficient of the turbine, the air density, turbine's sweeping area and of course the wind speed. the laws governing a WT are illustrated in equation (5) [42]:

$$P_m = c_p(\lambda,\beta)\times(\rho A/2)V_{wind}^3 \quad (5)$$

The per-unit values of (5) could be seen in equation (6), which uses the values of (7) and (8) to serve the illustrated coefficients. The $c_p - \lambda$ characteristics for different β values is available in [42].

$$P_{m\_pu} = k_p c_{p\_pu} V_{wind\_pu}^3 \quad (6)$$

$$c_p(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda_b} - c_3\times\beta - c_4\right)\times e^{\left(-c_5/\lambda_b\right)} + c_6\times\lambda \quad (7)$$

$$\frac{1}{\lambda_b} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3+1} \quad (8)$$

3-2-3 Energy storage system (ESS):

Pursuant to the rising trend of RESs utilization and distributed generation, the ESS has become an inseparable component of hybrid AC/DC microgrids. The main categories of ESSs and a prediction about the utilization cost of the batteries until 2020 are illustrated in Figure 7 [43]. Although the ESSs' penetration values in hybrid AC/DC microgrids are increasing, it can be inferred that the advances in battery technology will lead to less cost and higher efficiency values in the year 2020.

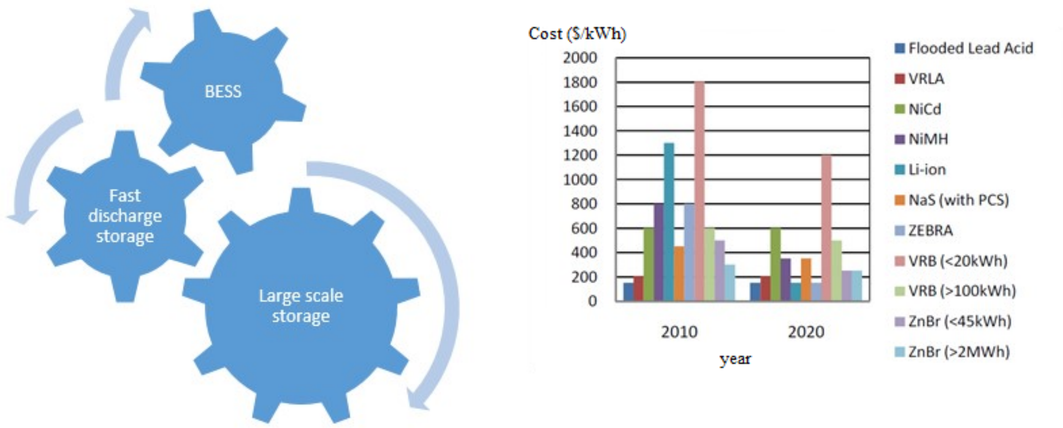

Figure 7. The main categories of ESSs and cost prediction of the batteries until 2020

3-2-3-1 **Mathematical modelling:**

The mathematical modelling of the three most common battery charging functions are shown in (9-11) [44-46]:

Lead Acid:

$$f(it,i^*,i_{bat},Exp)=E_0-K\times\left(\frac{Q}{Q-it}\right)\times i^*-K\times\left(\frac{Q}{Q-it}\right)\times it+Laplace^{-1}\left(\frac{Exp(s)}{sel(s)}\times\frac{1}{s}\right) \quad (9)$$

Lithium-Ion:

$$f(it,i^*,i_{bat})=E_0-K\times\left(\frac{Q}{Q-it}\right)\times i^*-K\times\left(\frac{Q}{Q-it}\right)\times it+AA\times Exp(-B\times it) \quad (10)$$

Nickel-Cadmium:

$$f(it,i^*,i_{bat},Exp)=E_0-K\times\left(\frac{Q}{|it|+0.1Q}\right)\times i^*-K\times\left(\frac{Q}{Q-it}\right)\times it$$
$$+Laplace^{-1}\left(\frac{Exp(s)}{Sel(s)}\times\frac{1}{s}\right) \quad (11)$$

In [47], lithium Ion and Lead acid batteries were compared from different aspects such as technical, economic and environmental effects on home appliances. It was concluded that the Lithium Ion batteries are more beneficial than the lead-acid batteries. Also, in [48] a review based on the comparison of Nickel-based batteries, lithium-based batteries and a combination of them has been performed in which, different charging algorithms are studied and a summary of the reviewed methods has been given.

There are also some other popular energy storage components that could be integrated into a hybrid AC/DC microgrid. Two of the main important components of this group are the supercapacitors and the flywheels [49]. Contrary to the batteries, the supercapacitors store the energy in the outer layer of the electrodes (instead of the electrochemical solution), which results in faster charge/discharge, enhanced lifetime and higher power densities. Moreover, the flywheels are most probably among the oldest of energy storage methods in the history, transforming kinetic energy into rotational energy of a flywheel with variable speeds, power densities and long lasting lifetimes. Table 4 presents the main characteristics of the ESS components [50]:

Table 4. Main characteristics of the ESS components

Technology Type		Power Density Mass ($W.kg^{-1}$)	Energy Density ($Wh.kg^{-1}$)	Total Capital Cost Per Unit of Power Rating (Euro. kW^{-1})	Charge/ Discharge Times	Lifetime	
						Years	Number of Cycles
Batteries	Lead-Acid	75-300	30-50	3254	s/h	5-15	2000-4500
	Li-Ion	50-2000	150-350	2746	m/h	5-15	1500-4500
Super/ Ultra Capacitors		800-1200	1-5	247	ms/m	5-8	50000
Flywheels		1000	5-100	1446	ms/m	15-20	20000-100000

3-2-4 Converter:

Because of the dependency of the hybrid AC/DC microgrids on the environmental and operational conditions they are usually bounded with distributed generation units. As previously mentioned, hybrid AC/DC microgrids can be operated in grid-connected or islanding modes. As discussed in the grid-connected mode, the voltage and frequency stability can be, to a large extent, guaranteed by the utility grid, but in case of unexpected events like faults as the system decides to move to the islanding mode, then the voltage, frequency and other power quality factors must be controlled by means of conversion. In this case, not only does the converter play a significant role in AC-DC or DC-AC conversion, but it can also be used as an interlinking unit. The control of power sharing is mainly performed by the droop control of both AC and DC sub-grids as presented in [51]. Also, as in [52], a fully controlled 3-phase rectifier has been used to connect the AC and DC microgrids. Moreover, in case it is preferred to control voltage levels, a pulse width modulation (PWM) controller is implemented on the rectifier.

Except for the main converter that couples the AC or DC sides, there are some other converters that facilitate the implementation of the hybrid AC/DC microgrids. One of them is the boost converter of the photovoltaic system [53]. Due to the dependency of the output power of the hybrid AC/DC microgrid on irradiance and temperature, the implementation of a maximum power point tracking (MPPT) system is essential and the integration of the boost converter would facilitate this, by regulating its output voltage.

The other converter is the bi-directional DC/DC converter of the battery bank as a part of the energy storage system. The buck/boost converter, which is controlled by the PWM method is connected to the main DC bus, as well as the battery, to control its charging current, depth of discharge (DoD), tracking the state of charge, etc.

One of the other converters used in hybrid AC/DC microgrids is the back to back AC/DC/AC converter, which is used along with the DFIG of the wind turbine. This converter has two main controlling objectives: i) controlling the active as well as reactive power on the stator, ii) stabilizing the DC link voltage. The operational modes of the mentioned converters have been fully covered in [54]. An extensive review of the configuration and implementation methods of single and parallel interfacing inverters that are used in hybrid renewable energy systems (HRES) is discussed in [55].

3-2-5 Electric vehicle (EV):

Considering the limited fossil fuel resources and the environmental issues, caused by the utilization of internal combustion engines (ICEs), the improvements in general microgrids' controlling technologies and the necessity to have mobile energy storages using electric vehicles is of great importance. In [56] different aspects of EV integration in microgrids have been analyzed. Various modelling procedures have been proposed by researchers, with a focus on different controlling aspects of EVs [57-61]. In order to have a clear view of the electric vehicles' role and their operations in microgrids, it is needed to know their operational status. As shown in Figure 8, [62] there are four possible conditions in this regard. In the 1st and 3rd states, the EV is in motoring mode since the torque and the speed have the same polarity and in case of reverse polarities, as in the 2nd and 4th states, we face backward generation (positive road slope) and forward generation (negative road slope). The ruling equations on a DC motor of an EV, which are normally used due to their controlling simplicity, are shown in Equations (12-19). These equations and the motivations for using DC motors in EVs are discussed in [63].

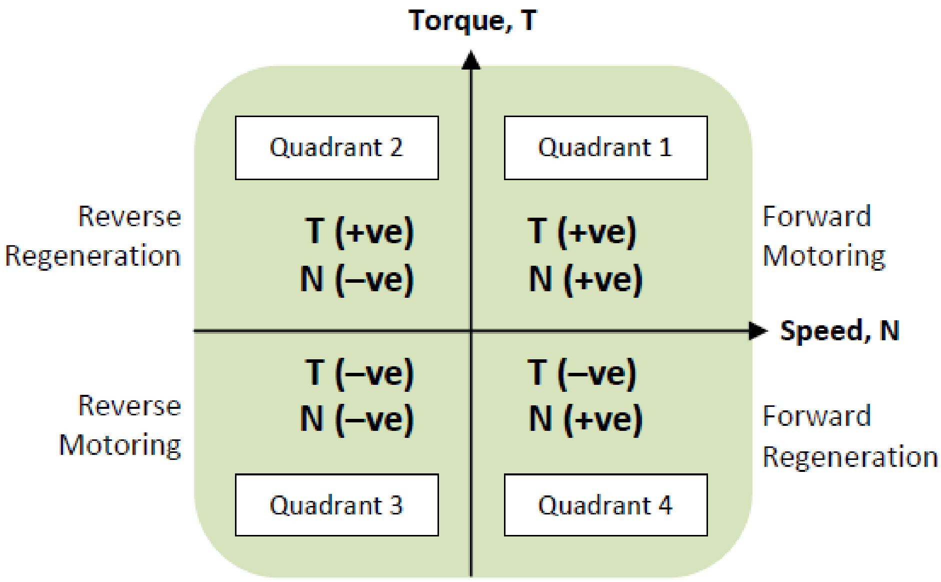

Figure 8. The possible operational status of an EV

$$T_d = K_m I_a \tag{12}$$

$$V_d = K_m \omega_d \tag{13}$$

$$V_H = I_H R_a + L_H \, {di(t)}/{dt} + V_d \tag{14}$$

$$V_H = K V_L \tag{15}$$

$$I_H = \frac{I_L}{K} \tag{16}$$

$$V_L = I_L R_a + E_B \tag{17}$$

$$B_{Err} = E_{B(actual)} - E_{B(calculated)} \tag{18}$$

$$K = (K_P + sK_I) B_{Err} \tag{19}$$

3-2-6 Micro Turbine (MT):

In order to meet the requirements of large loads and possess a dependable environment-friendly RES, a unit consisting of a gas turbine, a permanent magnet synchronous machine (PMSM), an inverter and a rectifier, which is referred to as MT, is used in microgrids. This unit could be utilized both in grid-connected and islanded modes and easily shift between these modes, which describes the popularity of MTs in recent years [64]. MTs owe their popularity to their various range of output power of 25kW to 500kW as well as their relatively small sizes. They are categorized, based on the layout configuration of their main components, into the single-shaft group and the double-shaft group. The single-shaft configuration is more common because of its higher rotation speeds and easier implementation. Reliability, especially during faults, integration of heat and power, and implementation facilitation are among the main advantages of MTs [65].

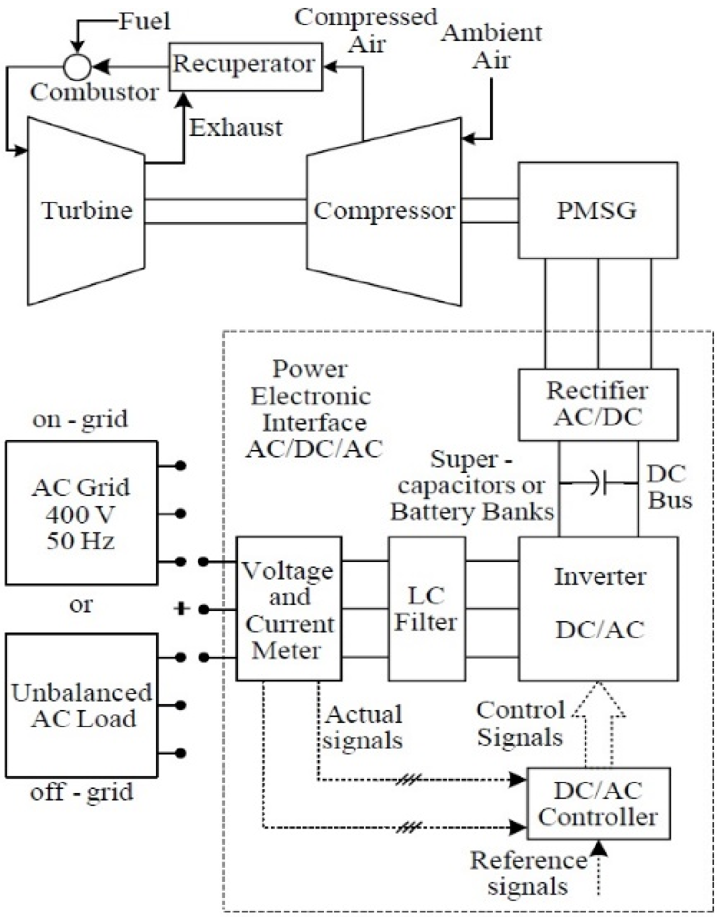

Figure 9. Simple schematic of a micro turbine [66]

3-2-7 Fuel Cell (FC):

One of the most efficient and environment-friendly components of a microgrid is the fuel cell (FC). FCs produce a low DC voltage as a result of the chemical reaction that happens inside them. Elimination of rotating parts has turned them into dependable and efficient resources. A fuel cell consists of four main parts: air flow system, hydrogen flow system, cooling and humidification. FCs are categorized based on the utilized electrolyte. The main schematic of a FC is illustrated in Figure 10. Also, different fuel cell types are compared in Table 5 [67, 68]:

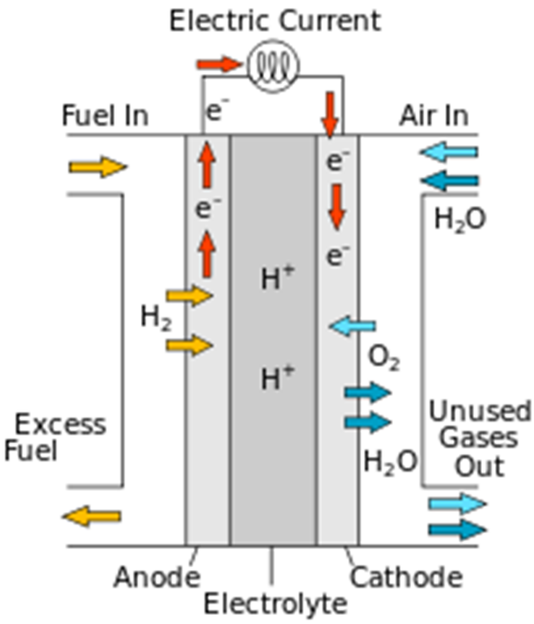

Figure 10. Fuel cell schematic [67]

Basically, there are five FC types as shown in Figure 11 [69]:

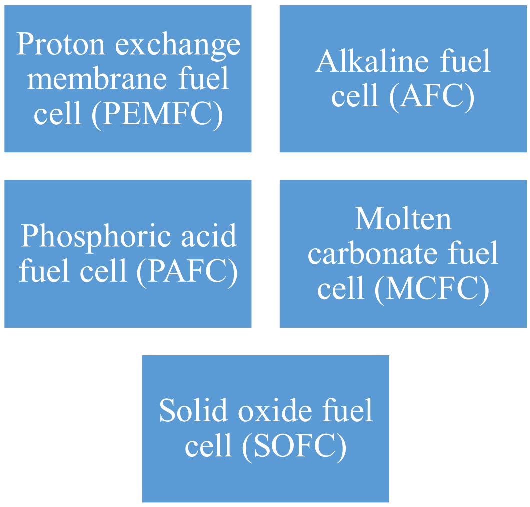

Figure 11. Fuel cell types' categorization

Table 5. Four main FCs and their characteristics

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Efficiency	Applications
PEM	Perfluorosulfonic acid	<120°C	<1kW-100kW	40-60%	Back-up power, Portable power, Distributed generation, Transportation, Specialty vehicles
AFC	Aqueous potassium hydroxide soaked in a porous matrix, or alkaline polymer membrane	<100°C	1-100kW	60%	Military, Space, Back-up power, Transportation
PAFC	Phosphoric acid soaked in a porous matrix or imbibed in a polymer membrane	150-200°C	5-400kW, 100kW module (liquid PAFC)<10kW(polymer membrane)	40%	Distributed generation
MCFC	Molten lithium, sodium and/or potassium carbonates, soaked in a porous matrix	600-700°C	300kW-3MW 300kW module	50%	Electric utility, distributed generation
SOFC	Yttria stabilized zirconia	500-1000°C	1kW-2MW	60%	Auxiliary power, Electric utility, Distributed generation

3-3 Conventional sources:

The conventional resources are the so-called traditional energy resources, such as: oil, gas and coal. They are categorized as nonrenewable energy sources, because of the limitations of the fossil fuel resources. Despite all the efforts that have been made to improve the efficiency of the combustion engines or any other machinery and equipment, these utilized resources are still polluting the environment more than ever. Despite all these facts, the hybrid AC/DC microgrid must always be integrated with conventional resources, because they act as a backup for a system that is highly dependent on unpredictable geographical phenomena.

4- Objectives and Constraints

The main goals in the operation and implementation of a hybrid AC/DC microgrid could be categorized into three major groups:

- Environmental
- Economic
- Technical

Hybrid AC/DC microgrids play an aggregation role in the integration of the demand and supply sides. Therefore, the environmental, economic and technical issues must be analyzed on both sides. The general purpose of the successful operation of a hybrid AC/DC microgrid is to improve the "social welfare" and since there is no criterion to measure this vague concept, cost and emission optimization would be defined and considered as equivalents for this term. For a better understanding of the aforementioned issues, consider Figure 12. The economic viewpoint consists of distribution system, micro sources and end users. The technical aspects are summarized in the constraints, and the environmental aspects could be modelled, considering the emission of green-house gases such as CO_2, SO_2 and NO_x [70].

Before starting to talk about the problem formulation and methodology of the operation, it is needed to know the practical environmental, economic and technical issues that must be solved, or at least be considered in a microgrid. From a technical point of view, there are several criteria, which distinguish the reliable technical operation of a microgrid, such as: SAIFI, SAIDI, ENS, voltage deviation and loss values. SAIFI is the system average interruption frequency index and SAIDI is the system average interruption duration index. One of the main reasons for defining such indexes is to have a clear insight into the system availability during repair and maintenance. Authors of [71, 72] have studied these indexes to analyze the proposed system reliability. One of the other criterions to evaluate the microgrid reliability is the ENS index. This term indicates the non-supplied energy value and could be used as a threshold in the design and operation of a microgrid especially considering peak loads during the primary designs and placement of DGs in the microgrid [73]. Another criterion in this regard is voltage deviation as investigated in [74, 75]. The importance of voltage deviation is completely clear, because it is used in the classical closed-loop control of active distribution networks with/ without microgrids. The last criterion is known to be the loss. Not only is this amount used as a criterion, but it is also used as one of the main objectives in some cases to improve the life-time of units, decrease the repairs cost, improve the power quality, etc.

The next step is to become familiar with the economics of the microgrids. Basically, aside from the cost functions defined by the analysis of any of the units of a microgrid, the cost definition could be reviewed from two viewpoints: the cost-based method and the price-based method. In the cost-based method there is a nonlinear term in the cost function of the dispatched units, leading to the independent performance of every unit and simplified control, as described in [76, 77]. In the price-based method as described in [78, 79] the pricing method has a dynamic nature and would change based on the network requirements, timing, load, etc., in which the retailers, Distribution Companies (Dis. Cos) and Generation Companies (Gen. Cos) play significant roles.

Superiority of any of these zones to the others is directly based on our expectations and requirements. Hence, if we are in the economic zone, meaning that economics plays the first role in our choices and also in scheduling and setting up the operational policies of the hybrid AC/DC microgrid. Therefore, the objective function in the economic zone, with regards to micro sources, costs and revenue is gained from the microgrid operation and the main constraints in this case are the physical limitations on both sides and the power balance limitations.

Technically speaking, the objective function mainly focuses on loss and cost minimization, considering all the economic zone constraints in addition to grid voltage and loading. Finally, from an environmental viewpoint, the objective function is mainly limited to cost and emission minimization and the constraints are still the same as those of the economic zone.

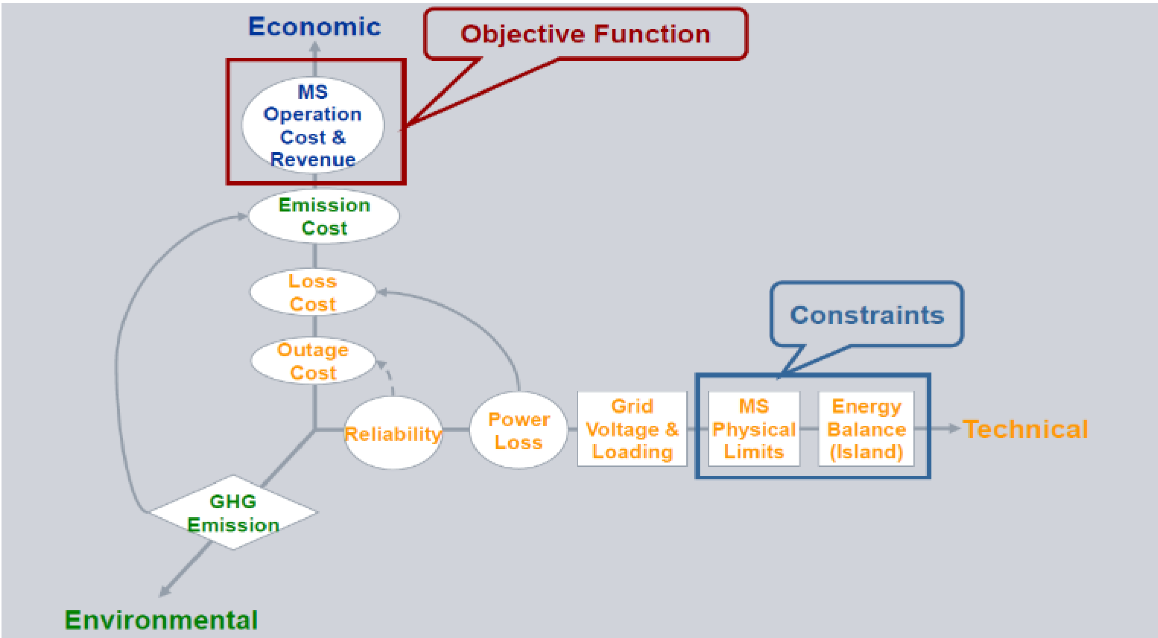

Figure 12. Economic zone of the hybrid AC/DC microgrid

As discussed above, the operation of a hybrid AC/DC microgrid could be modelled as a single/multi-objective optimization problem. This problem is normally the minimization of operation and maintenance cost of RESs and DGs, considering their technical, environmental and demand side constraints. There could also be a combination of the aforementioned zones, in which the limitations of both grid and micro sources are considered. This is simply the difference between defining a single or a multi-objective optimization problem [80].

The decision variable vector (X) of cost and emission minimization objective functions are defined as in (20-30):

$$X = [\overrightarrow{P_g}, \overrightarrow{U_g}] \tag{20}$$

$$\overrightarrow{P_g} = [\overrightarrow{P_{Grid}}, \overrightarrow{P_{Bat}}, \overrightarrow{P_{FC}}, \overrightarrow{P_{MT}}] \tag{21}$$

Note that since the energy policies rule that we obtain the maximum power from renewable energy sources, the wind turbine and photovoltaics' power are omitted from the decision variable vector.

$$\overrightarrow{U_g} = [\overrightarrow{U_{FC}}, \overrightarrow{U_{MT}}] \tag{22}$$

$$\begin{gathered}\overrightarrow{U_g} = [u^1_{FC_1}, u^2_{FC_1}, ..., u^T_{FC_1}, ...u^1_{FC_i}, u^2_{FC_i}, ..., u^T_{FC_i}, u^1_{MT_1}, u^2_{MT_1}, ..., u^T_{MT_1}, ...u^1_{MT_j}, u^2_{MT_j}, ..., u^T_{MT_j}] \\ g = \{1, ..., N_{WT}\},\ h = \{1, ..., N_{PV}\},\ i = \{1, ..., N_{FC}\},\ j = \{1, ..., N_{MT}\} \text{ and } T = 24\end{gathered} \tag{23}$$

$$\overrightarrow{P_{Grid}} = [P^1_{Grid}, P^2_{Grid}, ..., P^T_{Grid}] \tag{24}$$

$$\overrightarrow{P_{FC}} = [\overrightarrow{P_{FC_1}}, \overrightarrow{P_{FC_2}}, ..., \overrightarrow{P_{FC_i}}] \tag{25}$$

$$\overrightarrow{P_{FC_i}} = [P^1_{FC_i}, P^2_{FC_i}, ..., P^T_{FC_i}] \tag{26}$$

$$\overrightarrow{P_{MT}} = [\overrightarrow{P_{MT_1}}, \overrightarrow{P_{MT_2}}, ..., \overrightarrow{P_{MT_j}}] \tag{27}$$

$$\overrightarrow{P_{MT_j}} = [P^1_{MT_j}, P^2_{MT_j}, ..., P^T_{MT_j}] \tag{28}$$

$$\begin{gathered}\overrightarrow{P_{Bat}} = [\overrightarrow{P_{Bat_1}}, \overrightarrow{P_{Bat_2}}, ..., \overrightarrow{P_{Bat_k}}] \\ k = \{1, ..., N_{Bat}\}\end{gathered} \tag{29}$$

$$\overrightarrow{P_{Bat_k}} = [P^1_{Bat_k}, P^2_{Bat_k}, ..., P^T_{Bat_k}] \tag{30}$$

The cost minimization objective function could be defined as (31):

$$Min \quad f_1(x) = \sum_{t=1}^{T} Cost^t = \sum_{t=1}^{T} (Cost^t_{Grid} + Cost^t_{WT} + Cost^t_{PV} + Cost^t_{Bat} + Cost^t_{FC} + Cost^t_{MT}) \tag{31}$$

The emission minimization objective function is defined as (32). Even though the RESs have no emission added to the environment, the emission that is produced during the WT and PV manufacturing procedure is pollutant and must be taken into account as well.

$$Min \quad f_2(x)=\sum_{t=1}^{T} Emission^t = \sum_{t=1}^{T} \begin{aligned}[t] &[(\sum_{g=1}^{N_{WT}} P_{WT_g}^t \times Emission_{WT}^t)+(\sum_{h=1}^{N_{PV}} P_{PV_h}^t \times Emission_{PV}^t)+ \\ &(\sum_{i=1}^{N_{FC}} u_{FC_i}^t \times P_{FC_i}^t \times Emission_{FC}^t)+(\sum_{j=1}^{N_{MT}} u_{MT_j}^t \times P_{MT_j}^t \times Emission_{MT}^t)+ \\ &(\sum_{k=1}^{N_{Bat}} P_{Bat_k}^t \times Emission_{Bat}^t)+P_{Grid}^t \times Emission_{Grid}^t] \end{aligned} \tag{32}$$

In which the terms described in (33-38) illustrate the pollutant emissions per $kg.MW^{-1}$ and is a summation of CO_2, SO_2 and NO_x emissions. Note that the emission caused by WT and PV units are the emission that was produced in the production procedure of these units. Therefore, the values used in equation (32) are the average time-weighted values.

$$Emission_{Grid}^t = CO_{2_{Grid}}^t + SO_{2_{Grid}}^t + NO_{x_{Grid}}^t \tag{33}$$

$$Emission_{WT}^t = CO_{2_{WT}}^t + SO_{2_{WT}}^t + NO_{x_{WT}}^t \tag{34}$$

$$Emission_{PV}^t = CO_{2_{PV}}^t + SO_{2_{PV}}^t + NO_{x_{PV}}^t \tag{35}$$

$$Emission_{Bat}^t = CO_{2_{Bat}}^t + SO_{2_{Bat}}^t + NO_{x_{Bat}}^t \tag{36}$$

$$Emission_{FC}^t = CO_{2_{FC}}^t + SO_{2_{FC}}^t + NO_{x_{FC}}^t \tag{37}$$

$$Emission_{MT}^t = CO_{2_{MT}}^t + SO_{2_{MT}}^t + NO_{x_{MT}}^t \tag{38}$$

The main existing constraints in this regard are mentioned in (39-46):

- **Load Balance Constraint:**

$$\sum_{g=1}^{N_{WG}} P_{WT_g}^t + \sum_{h=1}^{N_{PV}} P_{PV_h}^t + \sum_{i=1}^{N_{FC}} u_i^t P_{FC_i}^t + \sum_{j=1}^{N_{MT}} u_j^t P_{MT_j}^t + \sum_{k=1}^{N_{Bat}} P_{Bat_k}^t + P_{Grid}^t = \sum_{l=1}^{N_l} P_l^t \\ l=\{1,...,N_l\} \tag{39}$$

- **Real Power Constraint:**

$$P_{Grid_{\min}}^t \le P_{Grid}^t \le P_{Grid_{\max}}^t \tag{40}$$

$$P_{Bat_{\min}}^t \le P_{Bat}^t \le P_{Bat_{\max}}^t \tag{41}$$

$$u_i^t P_{FC_{\min}}^t \le P_{FC}^t \le u_i^t P_{FC_{\max}}^t \tag{42}$$

$$u_j^t P_{MT_{\min}}^t \le P_{MT}^t \le u_j^t P_{MT_{\max}}^t \tag{43}$$

$$P_{MT_{\max}/FC_{\max}}^t = \min\{P_{MT_{\max}/FC_{\max}}, P_{MT_j/FC_i}^{t-1} + (UpRampRate)_{j/i}\} \tag{44}$$

$$P^{t}_{MT_{\min}/FC_{\min}} = \max\{P_{MT_{\min}/FC_{\min}}, P^{t-1}_{MT_j/FC_i} - (DownRampRate)_{j/i}\} \quad (45)$$

- **Battery Energy Balance:**

$$E^{t}_{Bat} = E^{initial}_{Bat} + \sum_{t=1}^{T} (U^{t}_{charge} \times P^{t}_{C\_Bat} \times \eta_c - U^{t}_{discharge} \times P^{t}_{Dch\_Bat} \times \eta_d) \quad (46)$$

The cost model and considerations of the aforementioned units are illustrated in (47-66):

- **Grid:**

$$Cost^{t}_{Grid} = C_{Grid} \times P^{t}_{Grid} \quad (47)$$

- **Wind Power [81]:**

$$Cost^{t}_{WT_g} = a_i + b_i \times P^{t}_{WT_g} \quad (48)$$

In which "a_i" and "b_i" are described as follows:

$$Cost^{t}_{WT} = \sum_{g=1}^{N_{WT}} Cost^{t}_{WT_g} \quad (51)$$

Or, as described in the grid cost section it could be calculated by multiplying the unit cost in the unit power as in (52):

$$Cost^{t}_{WT_g} = C_{WT} \times P^{t}_{WT_g} \quad (52)$$

- **Photovoltaic [82]:**

$$Cost^{t}_{PV_h} = a_i + b_i \times P^{t}_{PV_h} \quad (53)$$

$$Cost^{t}_{PV} = \sum_{h=1}^{N_{PV}} Cost^{t}_{PV_h} \quad (54)$$

"a_i" and "b_i" are the same as the values in (49-50), where $Cost^{t}_{PV}$ is calculated using equation (54) or it could be calculated as in (55):

$$Cost^{t}_{PV_h} = C_{PV} \times P^{t}_{PV_h} \quad (55)$$

- **Battery:**

$$Cost^{t}_{Bat_k} = (a_i + b_i \times P^{t}_{Bat_k}) + Cost^{t}_{Bat_{\deg}} \quad (56)$$

"a_i" and "b_i" are the same as the values in (49-50) and the $Cost^{t}_{Bat}$ is calculated using (57). The first term in (56) could be substituted by (58):

$$Cost_{Bat}^{t} = \sum_{k=1}^{N_{Bat}} Cost_{Bat_k}^{t} \tag{57}$$

$$Cost_{Bat_k}^{t} = C_{Bat} \times P_{Bat_k}^{t} \tag{58}$$

As described in [83, 84], the battery cost consists of a capital cost, which is equal to the first term in (56), and a degradation cost, which is mainly a result of the charge/ discharge cycles of the batteries. The main relations in this regard are as described in (59-61). The depth of discharge (DoD) of the batteries is a function of the battery type, which is defined by the Wöhler curve, where *K* and *p* are coefficients, modelling the battery type and the state index shows the state of the battery. The state could hold charge/ discharge/ Idle mode:

$$N_c(DoD) = pDoD_{state}^{K} \tag{59}$$

$$C_d(0, DoD_{state}) = \frac{CC_{Bat} \times DoD_{state} \times E_{Bat}}{N_c(DoD_{state})} \tag{60}$$

$$Cost_{Bat_{deg}}^{t} = \sum_{m=1}^{N_{discharge}} c_d^m (DoD_{initial}, DoD_{final}) \tag{61}$$

- **FC [85]:**

$$Cost_{FC}^{t} = 0.04 \times \frac{P_{FC}^{t}}{\eta} \tag{62}$$

Or, it could be calculated as in equation (63):

$$Cost_{FC_i}^{t} = C_{FC} \times P_{FC_i}^{t} \tag{63}$$

Where $Cost_{FC}^{t}$ could be inferred from equation (64):

$$Cost_{FC}^{t} = \sum_{i=1}^{N_{FC}} Cost_{FC_i}^{t} \tag{64}$$

- **MT:**

$$Cost_{MT_j}^{t} = C_{MT} \times P_{MT_j}^{t} \tag{65}$$

$$Cost_{MT}^{t} = \sum_{j=1}^{N_{MT}} Cost_{MT_j}^{t} \tag{66}$$

The format of the main optimization problem could change based on the problem formulation and the integrated units, as described in this section. Tables 6 to 10 [86-90], illustrate a comprehensive comparison among different types of fuel cells, PVs and battery technologies and their emissions that are to be addressed in the future:

Table 6. Efficiency comparison of different PV technologies [86]

Crystalline Silicon
Mono-Si, n-type (rear 79 cm^2 cell) → 26.7%
Mono-Si, n-type rear (module) → 24.4%
Multi-Si, n-type (4 cm^2 cell) → 21.9%
Multi-Si, p-type PERC (module) → 19.9%
Thin Film
CSIG (1 cm^2 cell) → 21.7%
CSIG (module) → 19.2%
CdTe (1 cm^2 cell) → 21%
CdTe (module) → 18.6%
a-Si, triple (1 cm^2 cell) → 14%
a-Si, triple (module) → 10.9%

Table 7. Energy Payback time comparison of different PV technologies [87]

Technology	**Mono-Si**		**Multi-Si**		**a-Si**		**μm-Si**		**CdTe**		**CSIG**	
Year	2011		2011		2008-2011		2013		2010-2011		2011	
Efficiency	14.8%		14.1%		7%		10%		11.9%		11.7%	
Scale of Production	~300 MWP		~300 MWP		33-45 MWP		120 MWP		963 MWP		20-66 MWP	
Energy payback time (year)	Italy	1.8	Italy	1.2	Italy	1.25	Italy	0.8	Italy	0.6	Italy	0.95
	Germany	3.3	Germany	2	Germany	2.3	Germany	1.5	Germany	1.2	Germany	1.7

The direct normal irradiance of Italy, Catania, Sicily case study: 1925 kWh/m^2/year

The direct normal irradiance of Germany case study: 1000 kWh/m^2/year

Table 8. Comparison of different FC technologies [88]

Parameters	**Fuel Cell Type**			
	PEMFC	**PAFC**	**MCFC**	**SOFC**
Electrolyte	Solid Polymer Membrane (Nafion)	Phosphoric Acid	Lithium and Potassium carbonate	Stabilized Solid Oxide Electrolyte (Yttria, zirconia)
Operating Temperature (℃)	50-100	~200	~650	~1000
Operating Pressure	15-30	~15	15-150	~15

(psig)				
Fuel	Pure H_2 (tolerates CO_2)	Pure H_2 (tolerates CO_2, approx. 1% CO)	H_2, CO, CH_4, other hydrocarbons (tolerates CO_2)	H_2, CO, CH_4, other hydrocarbons (tolerates CO_2
Oxidant	O_2 in air	O_2 in air	O_2 in air	O_2 in air
Efficiency	35-45%	40%	>50%	>50%
Cell Voltage (VDC)	1.1	1.1	0.7-1.0	0.8-1.0
Install Cost (US$/kW)	1,400	2,100	2,600	3,000

Table 9. Comparison of different battery technologies [89]

	Ni-Cd	**NiMH**	**Lead Acid**	**Li-ion**	**Li-ion Polymer**	**Reusable Alkaline**
Gravimetric Energy Density(Wh/kg)	45-80	60-120	30-50	110-160	100-130	80 (initial)
Internal Resistance (includes peripheral circuits)	100 to 200 6V pack	200 to 300 6V pack	<100 12V pack	150 to 250 7.2V pack	200 to 300 7.2V pack	200 to 2000 6V pack
Cycle Life (to 80% of initial capacity)	1500	300 to 500	200 to 300	500 to 1000	300 to 500	50 (to 50%)
Fast Charge Time	1h typical	2-4h	8-16h	2-4h	2-4h	2-3h
Overcharge Tolerance	moderate	Low	high	very low	low	moderate
Self-discharge / Month (room temperature)	20%	30%	5%	10%	~10%	0.3%
Cell Voltage(nominal)	1.25V	1.25V	2V	3.6V	3.6V	1.5V
Load Current - peak - best result	 20C 1C	 5C 0.5C or lower	 5C[7] 0.2C	 >2C 1C or lower	 >2C 1C or lower	 0.5C 0.2C or lower
Operating Temperature(discharge only)	-40 to 60°C	-20 to 60°C	-20 to 60°C	-20 to 60°C	0 to 60°C	0 to 65°C
Maintenance Requirement	30 to 60 days	60 to 90 days	3 to 6 months	not req.	not req.	not req.
Typical Battery Cost (US$, reference only)	$50 (7.2V)	$60 (7.2V)	$25 (6V)	$100 (7.2V)	$100 (7.2V)	$5 (9V)
Cost per Cycle(US$)	$0.04	$0.12	$0.10	$0.14	$0.29	$0.10-0.50
Commercial use since	1950	1990	1970	1991	1999	1992

Table 10. Comparison of different energy production units' emissions and its correlation with the growth of renewables [90]

Key figures to Denmark 2014-2016	Unit	2014	2015	2016
Power Generation (gross generation, including internal consumption)	GWh	32161	28931	30199
Power supply to the grid	GWh	30615	27704	28930
CHP generation	TJ	91330	93573	97881
Electricity imports	GWh	12702	15645	14976
Transmission grid losses (AC and DC)	GWh	876	963	969
Consumption (sale to distribution)	GWh	32594	32653	33018
Specification of net electricity generation				
Electricity from land-based wind turbines	GWh	7913	9300	8132
Electricity from offshore wind turbines	GWh	5165	4833	4650
Electricity from photovoltaic cells	GWh	597	605	744
Electricity from hydroelectric power	GWh	16	19	19
Electricity from biofuels	GWh	3078	2998	3508
Electricity from waste	GWh	1441	1438	1377
Electricity from natural gas	GWh	2188	1912	2366
Electricity from oil	GWh	126	151	169
Electricity from coal	GWh	10091	6449	7964
Emissions to air from electricity and CHP generation				
CO_2 (carbon-dioxide greenhouse gas)	Tonne	12561796	9678013	11118114
SO_2 (Sulphur dioxide-acidifying gas) total emissions	Tonne	2018	2533	2410
SO_2 from units <25 MW capacity	Tonne	1023	1626	1382
SO_2 from units >25 MW capacity	Tonne	995	907	10285
NO_x (Nitrogen oxides-acidifying gas) total emissions	Tonne	10096	9049	9819
NO_x from units <25 MW capacity	Tonne	5358	4795	5146
NO_x from units >25 MW capacity	Tonne	4738	4254	4673

Since there are few articles regarding the analysis of the hybrid AC/DC microgrids, we are going to review the main optimization methods of microgrids in the next sections.

Considering the fact that the operation of a hybrid AC/DC microgrid can be modelled by a single/ multi-objective optimization problem, the optimized operation of a microgrid can be analyzed from various viewpoints. In section 5, this problem is studied from the solution methodology aspects. In the next section, the uncertain parameters and the uncertainty modeling methodologies are reviewed. Finally, the existence of distribution grid in the optimized operation and the necessity to consider AC/DC power flow is analyzed. Table 11 illustrates a summary of the presented literature review.

Table 11. A summary of the presented reviews on solution methodologies, uncertainty modeling and AC/DC power flow

SOLUTION METHODOLOGY												
No.	MG Type					Solution Methodology						
	AC	DC	AC/DC	Grid-connected	Islanded	Method	Deterministic	Probabilistic	Single Objective	Multi Objective	Correlation	EV
[91]	×	×	✓	×	✓	Hybrid robust/ stochastic	×	✓	✓	×	×	×
[92]	×	×	✓	×	✓	Weighted majority algorithm	×	✓	✓	×	×	×
[93]	×	×	✓	✓	×	GWO	✓	×	✓	×	×	×
[94]	×	×	✓	×	✓	Genetic Optimization/ Generating sets search algorithm	×	✓	×	✓	×	×
[95]	✓	×	×	✓	×	Dynamic programming	×	✓	✓	×	×	×
[96]	×	×	✓	✓	×	Imperialist competitive/ Monte Carlo Simulation	×	✓	✓	×	×	×
[97]	×	×	✓	✓	×	Multi-objective genetic algorithm	✓	×	×	✓	×	×
[98]	×	×	✓	✓	×	Multi-objective genetic algorithm	×	✓	×	✓	✓	×
[99]	Smart microgrid			✓	×	Particle swarm optimization/ Q-learning	×	✓	×	✓	×	×
[100]	Smart microgrid			✓	×	Mixed Integer nonlinear programming	✓	×	×	✓	×	✓
[101]	×	×	✓	✓	×	IBM ILOG CPLEX	✓	×	×	✓	×	×
[102]	×	×	✓	✓	×	Cuckoo search/ Bat algorithm	✓	×	×	✓	×	×
[103]	✓	×	×	✓	×	NSGA II/ fuzzy clustering	×	✓	×	✓	×	✓
[104]	×	×	✓	✓	×	Stochastic programming/ CPLEX	×	✓	✓	×	×	✓
[105]	×	×	✓	✓	✓	Matlab/ Simulink	✓	×	✓	×	×	×
[106]	×	×	✓	✓	×	A novel two-step method (framework presented by the authors)	×	✓	✓	×	✓	✓
[107]	×	×	✓	✓	×	A* search/ AHP	×	✓	×	✓	✓	✓
[108]	Smart microgrid			✓	×	Decentralized control/ multi-agent	×	✓	✓	×	×	✓
THE MODELING OF UNCERTAINTY												
No.	MG Type					Uncertainty Modeling						
				Grid-			Probability	Single	Multi			

	AC	DC	AC/DC	connected	Islanded	Solution Methodology	density function/ uncertainty model	Objective	Objective	Uncertain parameter
[109]	×	×	✓	×	✓	Two-stage stochastic integer programming/ robust optimization	Latin hypercube sampling	✓	×	Renewable energy resources, electricity demand
[110]	×	×	✓	✓	×	Analytical hierarchical process	Real world values	✓	×	Solar radiation, wind speed, fuel price
[111]	×	×	✓	✓	×	Stochastic programming approach	Sub problem	×	✓	Load growth, component outage
[112]	×	×	✓	✓	✓	Robust optimization	Sub problem	×	✓	Load forecast error, renewable generation, market price, islanding
[113]	×	×	✓	✓	×	Genetic algorithm	Monte Carlo simulation	✓	×	Daily driven distance of PHEVs, load, electricity price
[114]	Cluster of microgrids			✓	×	Virtual power plant model and zone partitioning technique	Weibull distribution /Monte Carlo simulation	✓	×	Wind speed (Weibull), RESs generation
[115]	✓	×	×	✓	×	Clonal selection algorithm	2m-PEM	✓	×	Forecast error of active and reactive loads, power loss cost factor, customer interruption cost, failure rate, repair rate
[116]	✓	×	×	✓	×	Modified teaching learning algorithm/ fuzzy based clustering	2m-PEM	×	✓	Wind variation
[117]	✓	×	×	✓	×	Self-adaptive modifies honey bee optimization/ fuzzy based clustering	2m-PEM	×	✓	Forecast error of active and reactive loads, cost function coefficients
[118]	×	×	✓	✓	×	Modified firefly optimization algorithm	2m+1 PEM	✓	×	Power generation of wind and PV farms, market price, load demand
[120]	✓	×	×	✓	×	A novel P-OPF method	Gaussian mixture model/Chance constrained	✓	×	Wind power generation (Gaussian mixture model), active power output of conventional units, active power flow of transmission lines
[121]	×	×	✓	✓	×	Artificial bee colony/ improved differential evolution algorithm	Chance constrained	×	✓	Wind and PV generation, customer's load profile
[122]	×	×	✓	✓	×	Stochastic programming/ cuckoo optimization algorithm	Scenario-based	×	✓	Load consumption, available power of wind turbines and PVs
[123]	×	×	✓	✓	×	Improved teaching learning optimization algorithm	Scenario-based	×	✓	Load demand, PV & WT output power, market price
[124]	✓	×	×	×	✓	Particle swarm optimization/ self-	Scenario-based	×	✓	Load, wind power

						adaptive probabilistic mutation				
[125]	✓	×	×	✓	×	Probabilistic load flow	Unscented transformation	✓	×	Load, wind power
[126]	✓	×	×	✓	×	NSGA II	Unscented transformation	×	✓	Correlated loads

5- Solution Methodology

This section reviews some of the most common and effective solution approaches, utilizing heuristic and Meta-heuristic algorithms. Therefore, in section 5 the implementation of these methods in various case studies and different viewpoints are reviewed.

In [91], a new hybrid strategy for bidding optimization in an AC/DC microgrid based on stochastic/robust method has been proposed. Deterministic optimization assumes that the microgrid is in the islanding mode or takes a real-time market into account. In order to analyze the day-ahead market, a bidding strategy has been suggested. The main aims of this method are the optimization of battery charge/discharge status, procurement and selling of electricity cost and the dispatch of responsive loads and dispatchable resources. This is a 3-stage mixed integer linear programing (MILP) problem, regarding the imposed fees and constraints. The proposed method performs a more robust action against uncertainties in comparison to stochastic solution methodologies. The nonlinear objective function could also be converted into a mixed-integer linear form. Therefore, after the implementation of the proposed method on a WT/ PV/ FC/ MT/ DG/ BESS / responsive loads system, the operational status of the hybrid microgrid was considerably improved.

Considering the accessibility of the PVs and their relatively low initial investment cost, the single phase solar cells can be utilized at large scales. Therefore, their implementation and operational issues must be considered carefully. Also, with regards to the focusing on the pricing method of solar-based microgrids two main market bidding methods have been proposed in [92]. In this paper, the operation of an islanded microgrid is modeled using the Potluck Problem framework, which is a generalization of the Santa Fe Bar Problem. The novelty in problem formulation and finding the best bidding values using single-bid and double bid markets are among the valuable contributions of this paper.

In [93] the Grey Wolf Optimization (GWO) method was used to optimize the sizing of BESSs as the operation cost of a microgrid was being optimized. After considering the total operation cost and constraints, the GWO method was implemented on a microgrid. The main idea of this method comes from the hunting styles of grey wolves in nature. There is a hierarchical style among the wolves, categorizing them into four main groups. The αs are the leading groups and the βs follow them in the second stage, then there is δs, followed by the ωs in the lowest rank. The hunting steps could be categorized as followed: Encircling, Hunting, Attacking, and Searching. The GWO algorithm is implemented combined with a 14-step method to the defined microgrid and the results illustrate the superiority of this method on most optimization methods such as particle swarm optimization (PSO), Tabu search (TS), differential evolution (DE), Biogeography, Teaching- Learning and the Bat algorithm.

In [94] a microgrid consisting of PV and WT (special focus on modeling and uncertainty) is also subject to optimization, using the genetic algorithm (GA) and general set search algorithm. The multi-objective problem was to find the minimum GHG values as well as the expected ENS. The presented solution methodology has found a trade-off Pareto among optimized cost and reliability, which is a considerable contribution of this paper.

The power management optimization of a WT/BESS system is discussed in [95], in which the wind and load profiles are both predicted and the optimized operation of the system is established using the dynamic programming method. The prediction is performed in two different time domains. First, the long-term prediction is performed using a macro-scale dynamic programming. This prediction is based on the hourly wind speed and market price. The obtained dispatch is then revised using a micro-scale dynamic programming

In [96], a system consisting of WT/FC/PV/MT/ heat and electrical loads and resources is proposed. The optimal operation is established using a combination of Imperialist Competitive (IC) and the Monte Carlo (MC) algorithms. The problem is modeled on a nonlinear system, considering the technical, economic and environmental constraints. The IC algorithm consists of two main groups: the colony group and the imperialist group. The method philosophy is the same as that of GA and the PSO methods. After the implementation of the method, the system operational behavior is improved with regards to cost and run time. The important contribution of this paper is that the main objective is to minimize the summation of emission cost, O&M cost, installation cost of units and power interaction.

The DG/PV/BESS/WT system's optimization, using the multi-objective genetic algorithm (MOGA) to reach the optimized generation, considering the financial and technical constraints, has been analyzed in [97]. In this article an apartment has been chosen as a case study and the two main objectives were power availability maximization as well as cost and size minimization. Normally the MOGA is called the NSGA-II and is used to solve the problem of finding the best Pareto front. The main contribution of this paper is the consideration of home appliances and their role in peak shaving of the microgrid.

The NSGA-II was implemented on the system with and without considering the uncertainties (the uncertainty modelling could be found in [98]). The suggested method avoided oversizing and a relative trade-off was established. This article has performed a more practical review on the smart grids, in which the scheduling optimization of home appliances is analyzed. The main appliances and their load profiles are introduced with the objective function aiming at cost, energy and peak load profile minimization, subject to energy and timing constraints (unstoppable, stoppable and manual timing). This is a mixed integer programming (MIP) problem, with three scenarios and responses and it must be mentioned that in Linear Integer Programming (LIP) and Mixed Integer Linear Programming (MILP) problems there is no better answer that best suits the presented problem.

Similarly, a smart home consisting of a smart microgrid is analyzed to be optimized using the hierarchical demand response agents and the PSO algorithm in [99]. The battery and the environmental effects are closely studied in this article and the system consists of both electrical and thermal loads and resources. The objective is to improve the energy quality and reduce consumption cost. The contributions of this paper are using the Q-learning solution methodology to solve the charge/ discharge value of the BESS and considering demand response in the optimized operation framework. The same has been considered by the authors in [100], emphasizing the lifestyle in a smart home subject to operational optimization. The presented multi-objective optimization problem is formulated to find the minimized operation cost, maximized user convenience level and maximized thermal comfort level.

Article [101] discusses the optimization of the operation of commercial buildings that are integrated with microgrids. The objective functions include the imposed financial cost as well as the emission minimization. The proposed system includes both thermal and electrical loads and resources and since this was a multi-objective optimization problem the answer that represented a trade-off between the main objectives was chosen.

In [102], a combination of Cuckoo and Bat algorithms is implemented on a microgrid consisted of WT/MT/FC/DG/PV/BESS. This hybrid method showed successful results on the microgrid's operation. The presented solution methodology was validated against other algorithms such as firefly algorithm, ABC-ABC algorithm and the online management technique. The presence of thermal loads and the utilization of Matlab/ Simulink for modelling the system is among the interesting aspects of this paper.

Reference [103] analyzes the optimal operation of a microgrid in the presence of Plug-in Electric Vehicle (PEV), using NSGA-II algorithm. The addition of PEVs to the microgrid brings new challenges and opportunities to the microgrid operation. The new issues that must be dealt with are the charging/discharging status and the location of the PEVs in the network. The implementation of the suggested method has proved its effectiveness. Moreover, the authors in [104] have focused on the optimization of a system consisting of adjustable loads (such as EVs) and distributed generations (such as MTs and DGs), using the stochastic formulation of the optimization problem. Using real-world scenarios and the ability of the proposed framework to model customer behavior uncertainty is among the contributions of this paper.

Article [105] has studied both the grid-connected and islanded operation modes of a hybrid AC/DC microgrid integrated with a smart building. This article has focused on the optimal operation of distributed generation units and ESSs along with using the controllability of STATCOM devices. The results illustrate the successful optimized operation of the microgrid in deterministic framework. Moreover, in [106] a new two-stage method has been introduced. This paper points out that in the deterministic optimized operation of microgrids consisting of PVs and EVs the main assumption is that the output values are known. Also, even in probabilistic optimization of such microgrids the correlation of EVs, loads and PVs are not taken into consideration. Both of the aforementioned methods will lead to voltage and current probability function mismatch as well as decreasing the service quality. In order to solve such problems a correlated and coordinated method for optimized operation of a hybrid grid-connected microgrid is presented in this paper. Considering coordination among EVs, presenting a correlation model and using an unbalanced distribution system as the main case study are the most important contributions of this paper.

Article [107] has considered the coordination of EVs and renewable generations as the key to control stability and provide back up for the main grid. This paper focused on the reduction of spare renewable energy, providing required SOC for batteries, saving charging cost to EVs and supplying loads. The authors used the AHP method to sort priorities in the presented multi-objective problem. Each node of the presented microgrid is correspondent to an agent. The results reported by agents are gathered in a central memory. Afterwards, the A* search optimization algorithm is introduced to solve the problem. The modelling of EV travel and the required energy for making trips, along with using a novel optimization algorithm are a few of the contributions of this paper. Similarly, in [108] a decentralized control method has been introduced to provide a self-supporting backup for a microgrid in faulty conditions. Therefore, different agents are introduced for microgrid, home and EV and the behavior of the system is evaluated during outages or faulty conditions, subject to outage cost minimization. Controlling energy division among EVs can be considered as the main contribution of this paper.

6- The Modeling of Uncertainties:

A microgrid is subject to various types of uncertainties. The environmental uncertainties are caused by weather conditions and the geographical status of the microgrid, affected by the solar and wind profile. The economic uncertainties are mainly caused by the fuel price as well as load fluctuations. Therefore, several methods are developed to improve the precision of uncertainty modelling. Sometimes the uncertainty is not modelled with a probability density function (PDF) e.g. in [109] the authors have tried to solve the optimized operation problem of a microgrid, using the MILP methods, as the microgrid is subject to the uncertainties. The authors have modelled the uncertain parameters using the Latin hypercube sampling method. This method generates discrete scenarios and then they are reduced to a finite number of scenarios. In [110] the analytical hierarchical process (AHP) has been used to work on the optimum operation of a microgrid. This method is majorly used in multiobjective optimization problems to sort different possibilities in microgrid operation. This means that the AHP method assigns different criteria values of real-world data to e.g. environmental, economic or financial viewpoints and the operation of the microgrid is performed on that basis. Article [111] has analyzed the implementation of a stochastic programming method in optimized operation of an AC/DC microgrid with a special take on cost efficiency and safe operation. The authors have decomposed this problem into a master problem and a subproblem. The master problem focuses on cost minimization, while the subproblem is responsible for short-term operation cost minimization and system resiliency improvement. Similarly, in [112] a new method for the real-time marketing of microgrids has been demonstrated in accordance with uncertainties. The authors have indicated that the real-time market price is the main source of uncertainty in microgrid planning problem. Thus, the master problem focused on solving the main optimized investment problem and then in the subproblem the operational aspects were analyzed. In the subproblem, the worst case optimal operation over uncertainty are checked and if the answer is infeasible in the solution domain, an optimality cut reduces the problem domain to increase the convergence probability.

There are also some well-known methods to model the uncertainties that must be dealt with in a microgrid. Namely, they are the Monte Carlo (MC) method, the point estimate method (PEM), the scenario-based method, the chance-constrained method and the unscented transformation method (UT). The main differences among these methods are based on the generated sampling points, accuracy and run-time. The MC method e.g. has proved to be accurate since it generates a large number of sampling points for input uncertain parameters. Therefore, the output distribution becomes more accurate. In [113], the fact of EVs existence in microgrids has been analyzed, considering the associated uncertainties such as load, cost and parking distance. Therefore, the MC simulation method has been integrated with the genetic algorithm to solve this problem with detailed formulation. Also, article [114], has worked on evaluating the reliability of a distribution system, which could be contributed to a microgrid as well, either with a MC method to address the random nature of RESs or the two-level MC method to check the reliability of the microgrid or the grid itself. However, the run-time of this method is quite long due to the large problem dimensions. That is why other methods such as PEM were developed.

In [115] the attention was focused on enhancing the network reliability and using reconfiguration, whilst the corresponding uncertainties were fed to the system solver using the 2-PEM. In the Appendix of this paper PEM has been used to solve a simple mathematical example. Also, in [116] the multi-objective problem solution of emission and energy cost minimization in a wind/thermal system, using the PEM, considering the TLBO algorithm has been studied. In this paper, the uncertain parameters were accurately modeled using PEM. The results played a crucial role in generation scheduling of the proposed network. In [117], a modified PEM (2m) method has been integrated with a heuristic method to solve the multi-objective stochastic capacitor assignment to a network. The results showed the superiority of the proposed method in regard to convergence and iteration number. This method compared a few statistical information such as mean, variance, etc. of PDF to find the solution. In [118], an energy management system (EMS) was used to optimize the stochastic operation problem of a microgrid, consisting of PV and WT, using the PEM method. In this paper, the solar irradiation and wind profile uncertainties were taken into account. A precise description of the 2m+1 PEM is available in this paper.

As described in [119], considering a threshold value and trying to keep all the variables characteristics' values higher than that specific value, is the main aim of the chance-constrained method; otherwise, even the most optimized systems would not satisfy our requirements due to the uncertainties related to RESs. Moreover, the unit commitment problem, subject to wind power uncertainties was dealt with, using the chance constraint optimization method. Article [120] had a different view on the system analysis and tried to represent an OPF model, considering the system's uncertain nature by using the chance-constrained method. In this paper, an approximation of the output power of generation units' PDF is presented. Two constraints have been implemented on the output power of generating units to solve the OPF problem. Article [121] studied a new optimization platform, using the chance-constrained method, integrated with a series of heuristic methods, subject to load and RES changes. The main motivation for choosing this method is that it increases the reliability of solutions under certain confidence levels of inequality constraints.

One of the other methods for handling uncertainties is the scenario-based model, in which the random nature of cost and production are fed to the system based on a few pre-defined scenarios, regarding all the operational constraints as described in [122]. In this paper, the PVs and WTs output powers along with the load uncertainties are modeled using the stochastic scenario-based method, in which the scenarios were originally generated by the MC technique. Afterwards, based on the operational requirements of the system a probability value is assigned to each scenario and the scenario reduction was performed using the backward scenario reduction technique.

Also, in [123] the scenario-based uncertainty model is integrated with the modified TLBO method to solve the multi-objective optimized operation problem. First, the stochastic scenario-based framework is applied to the problem, in which the discrete control variables (here-and-now) are known. Afterwards, the continuous generation variables (wait-and-see) are generated by the scenario-based method. For runtime reduction the fine-tuning and the decomposition techniques were applied to the generated scenarios. Article [124] has studied the modeling of the intermittent nature of uncertainties associated with RESs using a scenario-based model, in which the scenarios are chosen by a roulette wheel to solve the dynamic economic emission multi-objective dispatch problem, using a PSO method to solve the reconfiguration problem.

The last method is called the Unscented Transformation (UT) method, which is mainly used in correlated nonlinear problems, in which a weight is associated to a proposed statistical characteristic of the variable and the final value is based on the updated value of these weights as described in [125]. The main motivation for utilizing UT method is its ability to model correlation among uncertain parameters without increasing computational burden. In [126] the authors focused on the effect of correlated loads on transmission network expansion planning. Using UT method the authors indicated that the runtime has considerably decreased in comparison with other methods, while the output results of the UT method have shown the same accuracy values.

7- AC/DC Power Flow:

The operation of microgrids is not limited to the minimization of maintenance and operation cost of DGs and RESs, or pollution minimization. It could also be investigated from the viewpoint of Load Flow (LF) and power flow (PF). The main purpose of solving the load and power flow problem is to control power losses and the corresponding cost minimization. First, we need to describe the fundamentals of the LF problem. Up to this point, we have only talked about active power amplitude in MWs, which is true but remarkably incomplete due to the complex nature of power values. The power in each node has an active and a reactive form and the amplitudes and the angles of the voltages in each node must therefore be controlled to enhance the operational performance of the microgrid. Now, we will review the latest studies in this regard. In this part, normal operational conditions are taken into consideration.

In [127], a semidefinite programming (SDP) method is implemented on an unbalanced microgrid to solve the multi-objective problem of power loss and cost minimization and the authors have claimed to have found the global optimal operation point using this method. Also, article [128] has used the same method on a smart grid, considering the points of common couplings and constraints of interfaces. In [129], the authors have established two operating modes on the back-to-back converter of the microgrid to control the power, which is a combination of load sharing and the power flow control. The proposed procedure showed efficiency during the feeding of various load types and islanding-reconnection modes. Article [130] has discussed the Linear-Quadratic-Gaussian (LQG) problem, corresponding to a network of microgrids (the case study assumed four microgrids and at least one of them had to be connected to the main grid and the rest were ought to have local connections) and controlling the power flow and the stored energy of the whole system. Despite the utilization of classic methods and a few assumptions to simplify the problem, the results are quite satisfying. As previously mentioned, the control of interfaces, such as inverters, would help solving the optimization problems of the microgrids. For this reason in [131] the authors have improvised a current controller that works on the basis of Lyapunov controlling procedure to attain OPF. Total Harmonic Distortion (THD) reduction, avoiding Park transformation, harmonic control and frequency independency are among the main features of this method. Articles [132, 133] have conducted a comprehensive general review on the various methodologies of inverter control to obtain OPF.

To this end, the reviewed literature was narrowed down to the normal operating modes of the microgrids. In [134], the accidental islanding modes of the inverter-based microgrids and the control of power flow in this case are studied. In [135], the authors have worked on a discrete genetic algorithm (DGA), which have been implemented on a microgrid, scheduling to reconfigure it for the sake of energy losses and switching cost minimization. The load flow equations of the proposed system have been computed and the optimal load flow (OLF) analysis was performed both in grid-connected and islanded modes. The superiority of this method has been illustrated in comparison to fixed-optimal or online operation of the microgrid. Reference [136] proposes a new method to study the effect of EVs improvising into microgrids' OPF studies using the Zloop method. Aside from setting up operating modes and electrical interfaces' control, another method to solve the OPF problem is the droop control of DGs. [137] has utilized the Newton Raphson method in this regard.

Thus, the importance of optimal planning and operation of the hybrid AC/DC microgrid has become quite clear. Hence, one of the most crucial points in this regard is the load flow analysis of the studied system. There are several variables in an electrical system that might affect this issue such as X/R ratio, existence of a slack bus, different loadings [138], connection to or isolation from the distribution network, unbalances etc. [139]. During grid connection, the load flow problem's solution could be divided into two main groups: 1) Derivative solutions such as Newton-Raphson, fast decoupled load flow, etc. and 2) Derivative-less solutions such as backward/forward sweeping (BFS) methods. The existing problems faced in the derivative solutions, were mainly related to the convergence and practicality issues. Therefore, in [140] the authors have defined a BFS algorithm, assuming that the distribution system, to which the microgrid is connected is radial so that the protection and analysis elaboration will be reduced.

The BFS algorithm has a simple procedure, in which it is primarily assumed that the voltages are known and the currents of all lines would then be found based on this assumption (the backward procedure). These currents would be subsequently used to modify the assumed voltages (the forward procedure). There are several variations of BFS algorithm, but the fundamentals are quite the same. As explained in [141], an AC droop-controlled microgrid is operating in islanding mode without having a slack bus. In this case, a modified BFS method was implemented on the microgrid to solve the load flow problem, which resulted in a fast and robust convergence. Moreover, in [142] a radial load flow analysis has been implemented on the PV and PQ buses of this network. It should be noted that the BFS algorithm proposes that all the existing buses have known values of active and reactive powers. The effect of unbalanced system on the load flow analysis procedure and the computational restraints have been studied in [143]. Modification of sensitivity matrices to calculate voltage and currents was studied in [144-146]. In [147], microgrids were introduced as an interface to integrate unbalanced loads into the AC and DC sides. The Ladder Iterative and the three-phase Newton-Raphson techniques are known to be conventional methods for handling unbalanced networks. However, they have some deficiencies, which are covered with a new π-Model of the interfacing AC-DC converter to attain unbalanced three phase power flow control. The authors in [148] have focused on presenting a method to study the power flow of a hybrid AC/DC microgrid in islanding mode. This paper proposes different controlling scenarios with regard to droop, distributed generation and configuration. The power flow problem formulation analyzes the network from the AC and the DC view point. One of the other power flow controlling methods is to utilize facilities to monitor and control the power flow in each phase of a microgrid, using a master/slave technique. This leads to enhanced power quality and line voltage amplitude as well as reduced losses [149]. Also, in [150] a method to control parallel interfacing converters has been proposed to deal with the unbalanced voltage phenomena.

8- Conclusion

In this comprehensive review of hybrid AC/DC microgrids the main parts of this microgrid were introduced and a comparison between different technologies in each section was made. The cost and emission minimization objective functions, decision variables and goals were subsequently clarified. Finally, different methodologies and viewpoints with regards to the operation problem formulation, subject to uncertainties related to RESs, as well as solutions to the power flow problems were analyzed.

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