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Microgrid: Architecture, policy and future trends

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ABSTRACT

Future electricity network must be flexible, accessible, reliable and economically viable to realise the aims of the smart grid initiative. In order to achieve these objectives and to reduce greenhouse gas (GHG) emissions, research on various configurations or architectures of microgrid (μGrid) systems is gaining greater attention. This is occurring in step with increasing penetration of Renewable Energy Sources (RES) such as solar, wind and other micro-sources. Energy storage can also be a part of the μGrid architecture to ensure more stable and sustainable operation. The techno-economic viability of the μGrid system is also a point of concern. Again, the variable and uncontrollable behaviour of RES can also introduce power quality problems. To improve the systems reliability, efficiency and power quality, different μGrid architectures are introduced. Complex control of the μGrid controller is helping to overcome these conditions. In that case, integration of Custom Power Devices is also playing an important role. Therefore, μGrid policies should also deal with these issues in the light of future trends towards the Smart Grid. This paper presents a literature review, based on various existing and/or simulated μGrid architectures. In relation to the reliability, efficiency and power quality issues, different distribution systems have been introduced. The advantages and disadvantages of these configurations are discussed here. The benefits of RES and its associated power quality problems have been identified. The benefits of energy storage systems and the development of communication systems towards the stable, flexible and efficient operation of smart grids are also reviewed. Findings have been outlined and then the policies with future trends of μGrid are also discussed.

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1. Introduction

Most of the large power generation systems rely on conventional energy sources such as coal, natural gas and oil, each of which have a more or less negative impact on the environment. Furthermore, as long-distance, high-voltage transmission lines carry power to the customers from centralized generation sources, transmission losses are unavoidable. The increasing demand for clean, reliable and affordable electrical energy is changing the existing scenario for electricity generation. The realization of the concept of the μGrid has the potential to deliver an innovative, economic and environmentally friendly solution. One of the major aims of the μGrid is to combine the benefits of non-conventional/renewable, low carbon generation technologies and high efficiency combined heat and power (CHP) systems. The choice of a DG technology mainly depends on the climate and topology of the region.

The μGrid embodies the concept of a single organized power subsystem comprising a number of distributed generation (DG) systems, both renewable (such as photovoltaic, wind power, hydro and fuel-cell devices) and/or conventional generation (such as internal combustion engines, micro-turbines and diesel generators) and a cluster of loads [1]. The application of an individual DG system is also possible, which is termed micro-generation (μGen). This can cause a number of problems such as local voltage rise, the potential to exceed thermal limits of certain lines and transformers, islanding problems and high capital costs. μGrid can be a better solution for those problems. Some of the benefits of μGrid, including enhanced local reliability, reduced feeder loss, better local voltage support, increased efficiency, voltage sag correction or uninterruptible power supply function are also reviewed in [2,3]. In μGrid, the DG system must be equipped with proper power electronic interfaces (PEIs) and control to ensure the flexibility to operate as a single aggregated system maintaining the power quality and energy output. μGrid central controller takes the leading role for satisfactory automated operation and control of μgrid while working in grid connected and islanded modes. Detailed of controller types and advancement in control technologies has been reviewed in [4]. From the grid point of view, the main advantage of the μGrid is that it is treated as a controlled entity within the power system which can operate as a single load. From the customer point of view, this μGrid can meet their electrical and heat requirement locally, can supply uninterruptible power, improve local reliability, improve PQ, reduce feeder losses and provide voltage support [5]. Furthermore the μGrid can reduce environmental pollution and global warming through utilizing low-carbon technologies.

Large scale penetration of distributed generation systems may cause also instability and thus it introduces a negative impact on the distribution grid or μGrid [6]. The aspects of stability in μGrid are also revised in [7]. Therefore control and operational strategies for individual and integrated distributed generation systems are highly important and these also have been studied in [8]. On the other hand, to avoid the grid voltage fluctuation or black outs at any time instant, the electric grid should be able to balance the power between the production and consumption. The power adjustment ensured by the excess capacity in stand-by mode, could be reduced if the peak consumption is shifted. Strategies for power management are being developed for a robust and reliable utility grid which can assist power balancing and avoid undesired injection and can perform peak shaving during peak hours [9]. To achieve this configuration, Smart Grid has been created that employs intelligent monitoring, control communication and self-healing technologies. Smart grid has mainly the following features: bidirectional power flow, bidirectional communication and reduces mismatch between production and demand [10]. As the concept of μGrid is for better penetration of RE in the existing grid that can help in energy management in more controlled way, can help in peak shaving and can reduce energy cost, it (μGrid) is considered as one of the possible approaches to develop a Smart Grid system [11]. This also depends on the design architecture of μGrid systems. In that case, understanding and predicting the impact of geographical location, resource availability and load demand on μGrid design is a must [12].

In recent years, emphasis has been placed on renewable energy based μGrid systems because of their advantages over μGen systems in terms of stability, reliability and economics. Different types of architectures and control strategies have been practiced (in real scale, test-bed or simulating platform) worldwide to achieve some specific goals. However, the commercial development of the μGrid system has not yet progressed significantly. The most common barriers were identified and grouped into four categories: technical, regulatory, financial and stakeholder [13]. Another obstacle is that these are not included properly in the national energy policy. Along with these, the policies relating to the implementation of μGrids differ from country to country. Most countries have not developed policies as yet and thus the goals for introducing μGrids as part of the existing electrical distribution network are not established. Power quality issues related to DG connected grid network are also a matter of concern. Reviews have already been done in different literatures and published papers with a focus on a specified part of the μGrid system. These include AC and DC technologies in μGrid systems, hybrid structures, islanding techniques, detailed in control with hierarchy approach and progress in protection. These are referred in the relevant sections of this paper.

Therefore, for integrating μGrid into the existing grid or to the future Smart Grid Network, this paper starts with the review of existing and simulated μGrid architectures that have been developed and studied to date. This study helps to identify the (i) basic structure and architecture of μGrid systems including the types of DG sources and storage, controller, power quality improvement and communication systems that have been used, (ii) operating policies and (iii) goals that have been achieved. Section 2 summarize this study by formatting a table for existing μGrid test-beds available in the literature together with their operating policies and goals. Based on the study, the basic μGrid architecture is divided into four parts (distribution systems, DG sources, storage, control and communication) that have been presented in Section 3. A brief overview along with the advantages and disadvantages of different distribution systems, DG sources including their power quality issues, storage systems and communication technologies are presented and are discussed in this section. Some of the common policies (with the focus on grid protection) and goals (with the focus on viability) which are being implemented in some countries are described in Section 4 and these have been correlated to the test-bed as discussed in Section 2. Section 5 discusses the findings from the existing μGrid systems. Concluding remarks and future trends of μGrid systems are also highlighted in the final part of the paper in Section 6.

2. Existing μGrid test-beds

Table 1 gives a comprehensive summary, available in the literature, of existing μGrid systems across the Europe, USA and Asia [14–53]. In the table example 1 to 39 is AC μGrid system, 40 to 42 is DC μGrid, 43, 44 is real-time emulated study and 45 is high frequency AC (HFAC) μGrid. It is to be noted that a review on μGrid test-beds around the world is also done in [54] where μGrids are divided into three types: facility, remote and utility, based on their respective integration levels into the power utility grid, impact on main utility, their different responsibilities, application areas and relevant key technologiesdoes. In addition, this paper emphasis on the capacity, type of sources, inclusion of storage, types of operating loads, control and communication techniques. The operating policies used to achieve the goal of the system are also highlighted in the table. These may help the other countries to decide their policy and goals. Finally references for each of the test-beds are also given in the table.

3. μGrid architecture

The basic architecture of a μGrid system is presented in Fig. 1 (a), which shows that a μGrid system generally consists of four parts: i) the distribution system, ii) the DG sources, iii) energy storage, iv) control and communications modules. Some of the details of each part of the system are discussed below.

The classification of μGrid systems is mainly based on the selection of the above components and the integration with the main electrical grid network. Fig. 1(b) shows the basic structure of this classification. With regard to grid integration, the μGrid system can be grid connected or isolated. μGrids can be operated as AC or DC distribution networks. Based on DG sources, both AC and DC μGrid can further be divided into three types - fully conventional, partially conventional/renewable and fully renewable. Both AC and DC systems can have energy storage devices incorporated. The AC μGrid can further be classified as line frequency or high frequency AC (HFAC) μGrid systems. Some of the details of this classification are also discussed in the following sections.

3.1. Distribution systems

In general, transmission and distribution systems and technologies are considered as AC and DC. Available technologies for μGrid system are studied in [55] where the line frequency AC and DC technologies are considered for transmission and distribution system. Research has also been carried out on high frequency AC system and thus there are three power electronics interfaces available by which the energy generated from the distributed sources can be connected to the distribution network. Therefore, the distribution network can also be classified as one of the following;

- DC line.
- 60/50 Hz AC line (line frequency).
- High frequency AC (HFAC).

3.1.1. DC line

Research on DC μGrid system is currently gaining in relevance. As most DG sources generate DC power and the DC distribution system has less power quality problems. The recent research work on DC μGrid system has been carried on in [55]. However, most loads are operated on AC system; hence there are many examples of DC distribution systems available.

- In the University of Bath (UK), a DC network has been set up for the Library and Learning Centre (LLC) consisting of 50 DC powered computers together with a central AC/DC converter and energy storage unit [56].
- Moixa energy: ‘Home Energy Server’ provides DC μGrid control and monitoring of AC devices [57].
- Horizone Fuel cell: Provides off-the-shelf fuel cell stacks from 12 W to 5 kW for DC bus [57].
- BOC (member of the Linde Group): DC micro sources (fuel cell) for off-grid μGrid [57].

Fig. 2 shows a DC μGrid system consisting of different DG units, storage and loads. Table 1 shows few existing DC μGrid systems in example 40, 41 and 42. Few advantages of DC μGrid over AC μGrid systems are as follows [49]:

- As the generated DC power is not converted to AC power, an inverter is not required for DC μGrid. Rather, only one grid connected inverter is required. Thus system losses and cost can be reduced.
- Each power supply connected to the DC grid can be easily operated in a co-ordinate manner.
- If the AC grid connection fails, due to an abnormal conditions or a fault, the DC grid system can be switched to stand alone mode.
- In the DC μGrid system experimental results show that, neither the circulating current nor current harmonics arises.

3.1.2. Line frequency (AC)

AC μGrid systems are operated at line frequency. The DGs are connected in a common bus in the μGrid system. The generated DC current from the DGs are transformed to 50 Hz AC by a suitable power electronics converter and then transmitted to the load side. Fig. 3 shows an AC μGrid system with different combination of DGs such as PV, wind, fuel cell and diesel. Battery has been used as storage system. Both AC and DC loads are being served. Most of the existing μGrid systems are AC μGrid, such as examples 1 to 39 in Table 1.

3.1.3. High frequency AC

Using high frequency AC (HFAC) to transmit electricity in μGrid systems is a new concept which is still under development. In HFAC μGrid systems, the DGs are connected to a common bus. The electricity generated by the DG is converted to a high frequency (typically 500 Hz) AC by power electronic devices and is transmitted to the load side. It is then converted to 50 Hz AC by an AC/AC converter. The load is connected to the distribution network, which can guarantee an effective interaction between the μGrid and the distribution network [59]. Table 1 includes one existing example of a HFAC μGrid system in No. 45. Fig. 4 shows a schematic diagram of an HFAC μGrid with two RESs and linear load.

HFAC μGrid systems can have the following advantages [60–63]:

- At higher frequencies, power quality improves because the harmonics of higher orders are easily filtered out.
- Improves efficiency is achieved by decreasing harmonic ripple current in electric machines.
- By tapping the ac link, auxiliary power supply units are easily available and they are smaller in size, having more efficiency.

Table 1
Example of existing, experimental and simulated μGrid systems.

Serial No.	Location	DG Sources	Storage	Load	Control	PQ control	Communication	Remarks/Policy	Reference
1	Bronsbergen, Netherland	PV	Battery	Res	Central	√	GSM	G1, G3, G5, G7, P1, P2	[5,14]
2	DISPOWER German	CHP, PV	Battery	Res	Agent based	√	TCP/IP	G1, G3, G5, G7, P1, P2	[15,16]
3	KesselUniv, German	PV, Wind, Diesel	Battery	Res, Com	Central	x	Ethernet	G1, G3, G5, G7	[15,17]
4	Mannheim, German	PV	x	Res	Not known	x	Not known	G1, G3	[5,18]
5	EDP, Portugal	CHP, Diesel	x	Com	Not known	x	Not known	G5, P1	[19]
6	Bornholm, Denmark	Diesel, Steam, Wind, Biogas	x	Static	Autonomous	√	Optical Fiber network	G1, G3, G5, P1,P2, P4	[20]
7	Samsø Island, Denmark	Wind, PV, Biomass, Geo	x	Res, Com	Not known	x	Not known	G2, G3, P5	[21]
8	Continuon, Netherland	PV	Battery	Res, Com	Central	Planning	Not known	G1, G3, G5, P1, P2	[22]
9	F.Y.R.O.M.- Kozuf	Waste water, Bio-gas	x	Com	Not known	x	Not known	G1, G3	[23]
10	Labein, Spain	PV, Wind, Diesel	Flywheel, Battery, SC	Com	Central	√	TCP/IP	G1, G3, G5, G7, P2	[24]
11	Kythnos Island, Greece	PV Diesel	Battery	Res	Central	x	Power line	G1, G5, G3	[25,26]
12	NTUA, Greece	PV, Wind	Battery	Static	Multi- agent	x	XML	G1, G3, G5, G7, P1, P4	[17]
13	Manchester, UK	Diesel	Flywheel	Static	Central	√	Not known	G7, P1,P2	[17,27]
14	CAT, Walse, UK	Hydro, wind, PV, Biomass	Battery	Not known	Central	x	Not known	G1, G3, G7, P1, P5	[28]
15	Boston Bar, Canada	Hydro, Diesel	x	Res	Autonomous	x	Telephone line	G3, G4, P1	[29,30]
16	Quebec, Canada	Steam Turbine	x	Res	Autonomous	x	x	G4, G3, P1	[30]
17	Ramea, Canada	Diesel, Wind	x	Not known	Autonomous	√	CSADA	G1, G3, G5, P2	[5]
18	Fortis-Alberta, Canada	Wind, Hydro	x	Not known	Not known	x	Not known	G1, G3, G7	[5]
19	GE μGrid, US	PV, Diesel, CHP	x	Com	Supervisory	√	Not known	G1, G2	[31]
20	CERTS, US	Natural Gas	Battery	Static	Autonomous	√	Ethernet	G5, G7, P2	[29,32]
21	Wisconsin Madison, US	Diesel	x	Static	Autonomous	x	x	Not known	[33]
22	Global Research, US	Wind, Diesel, PV, Fuel cell	√	Res	Central	x	Local control network	G1-G3, G5-G7, P1, P4	[5]
23	Berkeley, US	Oil, CHP	√	Com	Not known	x	Not known	G7, P5	[5]
24	Santa Rita Jail US	PV, Fuel cell, Wind, Diesel	Battery	Com	Not known	√	Not known	G1 – G7, P1 – P4	[34]
25	DUIT, US	PV, Micro-turbine,	x	Com	x	x	x	G1, P1	[35]
26	NREL, US	Not known	Not known	Res	Not known	√	x	P1, P2	[5]
27	Aichi, Japan	Fuel cell, PV	Battery	Ind, Res	Central	X	Telecommunication	G3, G5, G7	[36,37]
28	Kyoto, Japan	PV, Wind, Fuel cell, Gas	Battery	Res	Central	x	ISDN or ADSL	G1, G3, G4, G5, G7	[38]
29	Aomori, Japan	Gas, PV, Wind, Wood	Battery	Com, Ind	Central	√	Private distribution line	G2, G3, G5, P1, P2, P3, P5	[5,29,38]
30	Sendai project, Japan	PV, Fuel cell, Gas	Battery	Res, Com, Ind	Central	√	x	G1, G3, G7, P2	[38,39]
31	Shimizu, Japan	Gas	Battery, Cap	Com	Not known	√	x	G7, P2	[5]
32	HFUT, China	PV, Wind, Hydro, Fuel cell, Diesel	Battery, Ultra-Capacitor	Static	Local, Central	√	x	G1, G3, G7, P3, P2	[40]
33	Labscale, China	PV, Wind	Battery	Static	Central	√	RS485 line	G3, G4, P1	[41]
34	IET, India	Fuel cell, Diesel	Not known	Static	central	√	Not discussed	P2	[42]
35	Benchmark μGrid, Greece	PV, CHP, Wind, Fuel cell	Battery, SC Flywheel	Res	Central/Autonomous	x	x	G3, P1	[43,44]
36	2-DG μG, Japan	Synchronous gen	x	Static	Autonomous	√	√	P2	[45]
37	Conv-fed, Japan	Not known	Not known	Static, motor	Autonomous	√	Not known	P2	[46]
38	Tokyo, Japan	PV, Wind, Biogas	Battery	Com	Not known	√	Not known	G3, P2	[5]
39	Girona, Spain	PV, Wind, Diesel	Battery	Com, Res	Central	x	Zig Bee	G1 – G7	[47]
40	DC linked μG	PV, Fuelcell	Battery	Res	Autonomous	x	x	G3, G7	[48]
41	Japan	PV, Wind	Battery	Not known	Autonomous	x	x	G1, G2, G3	[49]
42	CESIRICERCA Italy	PV, Wind, CHP, Diesel	Battery, Flywheel	Static	Central	√	2.4 GHz radio channel	G2, G3, G5, G7, P2	[15,50]
43	IREC's μG, Spain	Wind, PV	Bat, SC, Flywheel	Com	Autonomous	x	Ethernet TCP/IP	G3, G4, G5, G7, P1, P3	[51]
44	CRIEPI, Japan	PV	x	Not known	Central	x	Fiber optic	G3, G7	[29,52]
45	Texas, US	Gas-turbine	X	Not known	Autonomous	√	x	G1, G5, P2	[53]

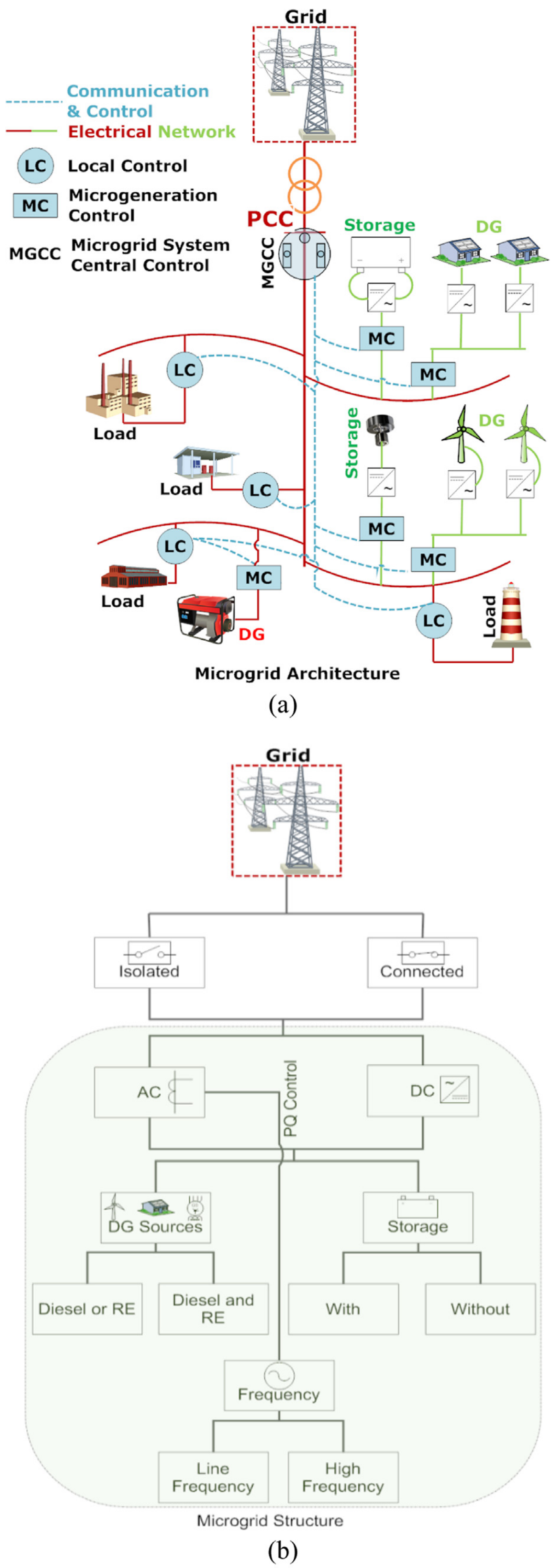

Fig. 1. (a) Microgrid architecture and (b) microgrid Structure.

- HFAC μGrid can effectively improve brightness and power efficiency of lighting equipment.
- High frequency power transformers and other passive circuit components become smaller.
- High frequency resources are easily connected to flywheel units.
- Storage units are easily connected to the HFAC-based μGrid, improving stability and reliability.

The disadvantages of HFAC μGrids are as follows [59]:

- HFAC increases line reactance and increases power loss which limits the energy transmission distance.
- HFAC causes a large voltage drop along the line.
- Control devices are relatively complex for HFAC system.

Table 2 shows some features of DC bus, AC bus and HFAC bus systems configured as μGrids. A number of merits and demerits together with applications of these three systems are identified. In the case of merits, it is identified that the DC bus has higher reliability, lower losses, less power quality problems and no power converter is required. The AC bus has better reliability, easier connection to the utility grid and lower average cost; HFAC bus has fewer PQ problems, lower volume and weight.

3.2. Distributed generation resources (DG)

Distributed generation (DG) technologies applicable for μGrid may include a range of technologies: wind power system, solar photovoltaic (PV) system, hydro power system, geothermal energy, biogas, ocean energy, single-phase and three-phase induction generators and synchronous generators driven by IC engines [64]. From the review of existing μGrid test-beds it is found that the most commonly used DG sources are PV, wind, micro-hydro and diesel. Biogas and ocean energy are also being used in some of the test-beds. A brief description of the most widely used DG sources is given below.

3.2.1. Photovoltaic (PV) system

Solar PV generation involves the generation of electricity from solar energy, which is free and inexhaustible. The overall performance of a PV system depends on the (i) geo-location and resource information such as solar intensity, cloud cover and temperature; (ii)system efficiency of PV modules, DC-DC converters and the inverters together with their controlling mechanism. Fig. 5(a) shows the simple structure of a grid-connected PV system. Fluctuation in irradiance and cloud cover plays a vital role in creating voltage disturbances. This disturbance can disconnect the inverter from the grid and thus can cause loss of energy supplied. Considering the long term performance, PV systems show a remarkable degradation of efficiency due to the variation of the source and performance of the converter [66].

3.2.2. Wind turbines (WT)

Wind Energy Conversion System (WECS) converts wind energy to electrical energy. WECS has been popular for many years. The basic structure of a wind power system is made of two parts: one mechanical and one electrical. In the mechanical part, rotational energy is extracted from the kinetic energy of the wind and in the electrical, part the rotational energy is transformed into electric energy. The main part of the wind turbine is the tower, the rotor and the nacelle. The nacelle accommodates the mechanical power transmission components and the electrical generator. The rotor may contain two or more blades. The wind turbine captures the kinetic energy of the wind through the rotor blades and transfers the energy to the electrical generator through the gearbox. The generator shaft is driven by the wind turbine to generate electrical power. Wind turbines may have a horizontal axis or vertical axis

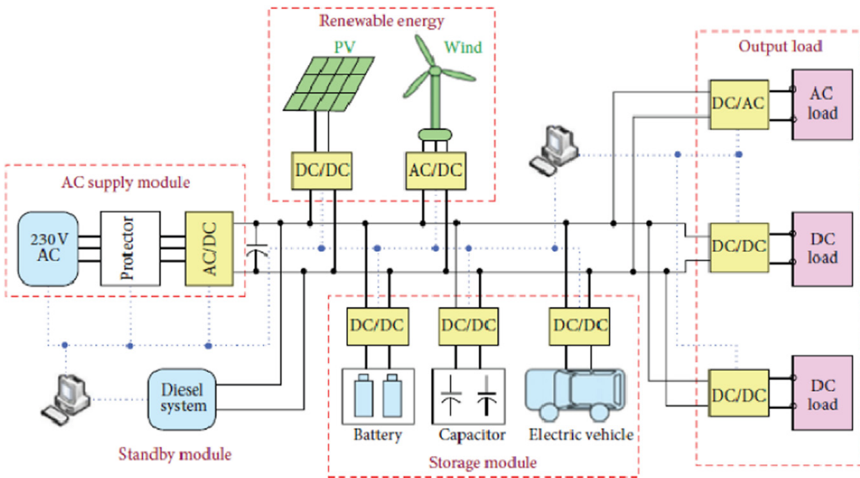

Fig. 2. DC μGrid system [58].

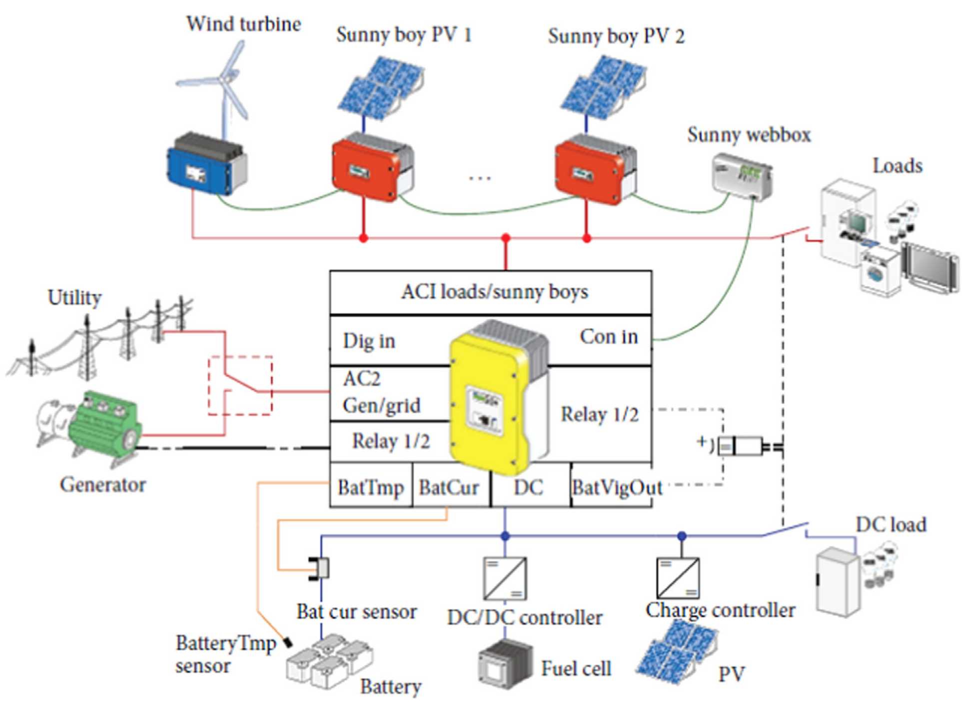

Fig. 3. AC μGrid system [58].

configuration. Fig. 5(b) shows the configuration of a WECS with battery storage.

3.2.3. Micro-hydro

Micro-hydro is a generation technology that produces electricity from the flow of water. This energy generation system depends on the topography and annual precipitation of the area. In the absence of significant hydro storage, the system suffers from large variation of water flow due to uneven rainfall and results in variation in generation. Run-of-river systems are often used in micro-hydro power systems which do not require a large storage reservoir. A portion of river water is diverted to a water conveyance – channel, pipeline or penstock which delivers it to the turbine or water wheel which drives the shaft. The motion of the shaft can be used for mechanical power such as pumping water. This can also be used to power a generator to produce electricity. Fig. 5(c) shows a grid connected micro hydro system.

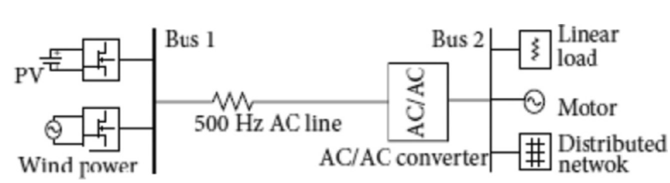

Fig. 4. HFAC μGrid schematic [63].

Table 3 shows some characteristics of common DG sources. Some of the advantages of renewable energy based DG sources are as follows:

- Sustainable and natural energy sources.
- Positive environmental impact.
- Reduced electricity consumption from conventional sources.
- Reduce GHG emission.
- Longer life time.

Table 2
Features of DC bus, 60/50 Hz AC bus and FHAC bus [65].

Interface type	DC bus	60/50 Hz AC bus	HFAC bus
Merits	good reliability; lower loss; longer grid length, lower costs; high power density due to elimination of magnetic transformer; less PQ issues are present; power conversion technology is not required; ac-grid connected inverters are needed for interfacing with grid	good reliability; easier connection to the utility grid; possible galvanic isolation; easier adjustment of voltage levels; lower average costs;	Lower volume and weight; improvement of fluorescent lighting; direct connection of high frequency motors and compressors; smaller passive element; galvanic isolation with smaller high frequency transformers
Demerits	High volume and weight due to presence of electrolytic capacitors in DC link; less compatibility of voltage levels; higher corrosion of electrodes; no galvanic isolation; few loads are operated in DC power systems. So implementation of DC μGrid is very limited	High volume and weight; stringent synchronization requirements; current recirculation between sources; higher load effects; reduced grid length; galvanic isolation with bulky line frequency transformers; PQ problems are present; power conversion technology is needed	Smaller grid length; higher cost; complexity of design and control; increase in voltage drops and power losses in the line
Application	Renewable sources with DC output	Renewable sources with variable AC output; direct connection through induction generators; requirement for galvanic isolation	Any renewable sources; requirement of smaller volume and weight and higher power density

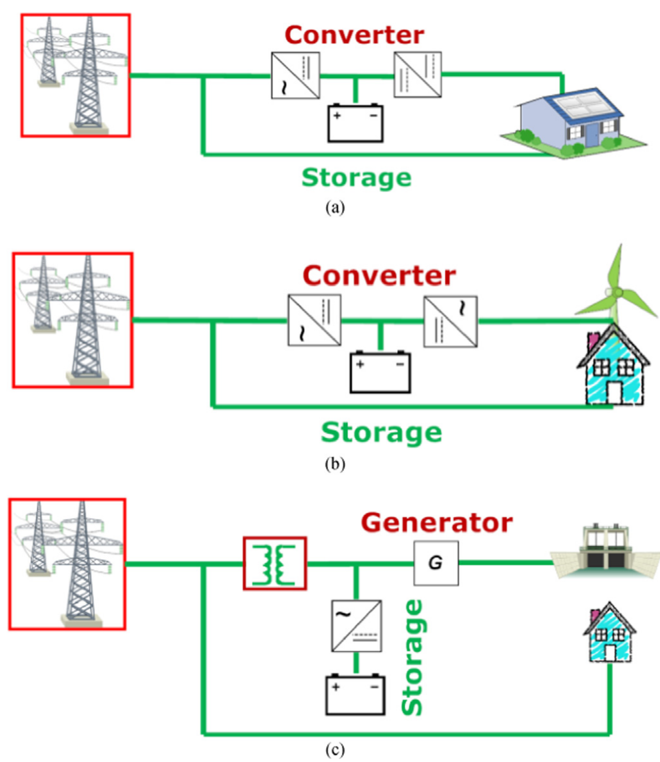

Fig. 5. Basic structure of grid connected (a) solar PV (b) wind (c) micro-hydro system.

- Silent operation (except wind and hydro).

These DG sources can be effectively used in μGrid system, yet they have some disadvantages:

- High installation cost.
- Low energy efficiency.
- Restriction to certain geographic areas and/or weather conditions.

3.2.4. Power Quality (PQ) issues related to DG sources

Power quality in μGrid systems has become an important issue as the penetration of DG sources, either connected to the grid or as part of a μGrid. Solar, wind, micro-hydro and diesel are the leading DG sources. Power quality problems related to these DG sources have been identified in [69,70] and are shown in Table 4.This table shows that, Renewable Energy Sources (RES) solar PV and wind energy systems causes almost all the PQ problems such as voltage sag/swell, over/under voltage, voltage and current harmonics and flicker. Compared to PV and wind, small/micro hydro systems have fewer power quality problems. The main advantages of these RESs are they are pollution-free. Conventional diesel generation also has fewer power quality problems such as voltage sag/swell, over/under voltage and flicker. The main disadvantage of this source is that it emits CO_2which pollutes the environment. Table 1 shows that few μGrid test-beds have implemented power quality devices in their systems. At the same time, for stability and reliability of the system, PQ control including fault management is one of the basic criteria to be considered and therefore more emphasis should be given to improving PQ problems in DG resources and μGrid [68].

3.3. Storage devices

One of the main requirements for successful operation of a μGrid is inclusion of energy storage devices, which balances the power and energy demand with generation. Energy storage devices perform the following functions [65]:

- Ensure power balance in a μGrid despite load fluctuation and other transients. DGs with their lower inertia have less capability to respond to these disturbances.
- When there are dynamic variations in intermittent energy sources, they provide ride-through capability and allow the DGs to operate as dispatchable units.
- Provides the initial energy requirement for a transition between grid-connected or/from islanded operation of μGrid.

When a new load comes on line, it results a slight change in system frequency [71]. A μGrid system with several DG sources designed to operate in an island mode must provide storage options to ensure energy balance [2]. Due to the large time constants (from 10 to 200 s) of the responses of some DG, such as fuel cell and micro-turbines, storage devices must be able to balance the power following system disturbance and/or significant load changes [71]. In case of sudden system changes such as load-following situations, these devices act as AC voltage source. As these devices have physical limitations, they can store a finite capacity of energy. The backup energy storage devices must be included in μGrid to ensure the uninterrupted power supply. Through these actions, the storage system also helps to increase the μGrid stability and thus helps to improve the power quality.

There are four types of energy storage methodologies have been developed so far and these are: (i) chemical – battery and fuel cell, (ii) electrical - superconducting magnetic energy storage

Table 3
Typical characteristics of common DG sources [67,68].

Characteristics	Solar	Wind	Micro-hydro	Diesel
Availability	Geographical location dependent	Geographical location dependent	Geographical location dependent	Any time
Output power	DC	AC	AC	AC
GHG emission	None	None	None	High
Control	Uncontrollable	Uncontrollable	Uncontrollable	Controllable
Typical interface	Power electronic converter (DC-DC-AC)	Power electronic converter(AC-DC-AC)	Synchronous or Induction generator	None
Power flow control	MPPT &DC link voltage controls (+P, ±Q)	MPPT, Pitch and Torque control (+P, ±Q)	Controllable (+P, ±Q)	Controllable (+P, ±Q)

Table 4
PQ problems related to DG systems [69,70].

PQ Problems	Wind Energy	Solar Energy	Micro/ Small Hydro	Diesel
Voltage Sag/Swell	•		•	•
Over/Under Voltage	•			•
Voltage Unbalance		•		
Voltage Transient	•			
Voltage Harmonics	•	•	•	
Flicker	•	•		•
Current Harmonics	•	•	•	
Interruption	•	•		

(SMES) and super or ultra-capacitor, (iii) mechanical - pumped hydro, flywheels and compressed air energy storage (CAES) systems,(iv) thermal energy storage - super-heated oil or molten salts. The most commonly used and suitable storage devices for μGrid are batteries, flywheels, fuel cells and super-capacitors [72–74]. Therefore, a brief description of these storage systems is presented below.

3.3.1. *Battery*

Batteries store energy in chemical form during charging. When connected to the load it discharges that stored energy in electrical form. Storage in a μGrid system can be mounted on the DC bus of each micro-source separately or can be used as a central storage system. Batteries are comparatively cheaper than other storage devices and it has the extra benefit of being able to reserve energy for future demand. That is why it is quiet popular as μGrid storage system. Lead-acid batteries usually provide a large current for a short time interval and thus it is the most suitable storage option for μGrid applications [75]. At present, NaS batteries are used for wind farm support (for example, East Busco Substation, USA, 1 MW, 6MWh) and to smooth the output of PV systems [76].

3.3.2. *Flywheel*

Flywheels stores kinetic energy in a rotating mass and releases it by converting the kinetic energy to electrical energy as required, thus reducing the speed of rotation. Their application has mainly been for power quality improvement and to provide energy for UPS [76]. There are very few examples of flywheels in demonstration μGrid system. They can be used as central storage for the whole system.

3.3.3. *Super-capacitor*

Super-capacitors store energy in the form of their electrostatic field. Due to their structure of liquid and porous electrodes, an extremely high specific surface area is obtained. Furthermore, extremely short distance exists between the electrode and electrolyte (less than 1 μm). These two factors help to develop a very high capacitance per unit of volume, which is between hundreds to thousands times larger than electrolytic capacitors [77]. The main advantages of super-capacitor are as follow; (i) no moving parts, (ii) requires neither cooling nor heating, (iii) no internal chemical changes during operation, (iv) robust and very efficient and thus reaching a cycle efficiency of 95% or more. Unfortunately, the most important disadvantages of super capacitor are (i) the high cost and (ii) limited capacity.

3.3.4. *Fuel cells*

Fuel cells could be another option for energy storage as they directly convert chemical energy of a fuel into electrical energy. Due to higher efficiency and lower fuel oxidation temperatures, fuel cells emit less CO_2 and NOx per kilowatt of power generated. As there is no moving part, they are almost free from noise and vibration and are robust and require low maintenance. The output of the generator is 1 kW to 10 MW. Electrical efficiency is 30–60% and overall efficiency is 80–85%. This makes fuel cells suitable for urban and suburban locations. Moreover, they can use a variety of fuels such as natural gas, propane, landfill gas, anaerobic digester gas, diesel, naphtha, methanol and hydrogen [78,79]. Another innovative energy storage has introduced by the RAPS Pty Ltd, based on highly pure graphite blocks. These blocks can be heated by the DG sources or the grid and can be used later. Furthermore this energy can be used to produce steam through embedded heat exchangers and can be converted to electricity with steam turbine generators [80]. The range of the storage capacity of the graphite is from around 300 kW h (thermal) per ton at a temperature of 750 °C upto 1000 kW h (thermal) per ton at 1800 °C [81]

Depending upon the capacity, performance, purpose of use and future scope, detailed comparative studies among the different types of storage devices can be found in [82]. Some of the basic features of these storage devices are also given in Table 5. From Table 1 it is observed that most commonly implemented storage devices in the μGrid test-beds are various types of batteries, flywheels and ultra/super capacitors. Few of the test-beds did not include storage units. It was found that if the μGrid is without storage, a controllable DG source should be included in the system such as a diesel generator. This can be observed in examples 5, 6, 15, 17, 20, 22, 24, 25, 32, 39 and 35. There are two exceptions where no storage device is included in the system and only uncontrollable DG sources are present in examples 4 and 18. In these cases grid integration is an important factor.

3.4. Communication systems

For power control and protection, communication systems are very important. The basic communication methods with their characteristics are given in Table 6. Details of the advantages and disadvantages of these systems together with the protocol have been discussed in [83]. From the following table it is observed that the communication systems commonly applicable in the μGrid systems are GSM, GPRS, 3 G, WiMax, PLC, ZigBee. Among the systems mentioned, 3 G and WiMax have fast data transfer rate and long coverage range. But the limitation is that spectrum fees are costly. In PLC communication systems, data rates are in the range of 2-3 Mbps and coverage ranges between 1 and 3 km. For long distance communication, WiMax and 3 G are used and for short distance communication PLC and ZigBee systems are preferable. Table 1 shows that different μGrid test-beds have implemented different types of communication systems. Amongst these Wireless Sensor Network could be a viable option for μGrid systems.

Table 5
Basic features of suitable storage devices in μG system [58].

Basic features	Battery	Flywheel	Super capacitor
Continuous power (W/kg)	50–100	200–500	500–2000
Typical back up time	5–30 min	10–30 s	10–30 s
Losses at stand-by	Very low	Variable	High
Environmental impact	Medium–High	Low	Low
Maintenance	1/year	1/5year	None
Charging efficiency (%)	75–95	90	85–95
Current energy price ($/kWh)	150–800	3000–4000	4000–5000
Service Life (year)	5	20	> 10

4. Policy and goal

Most of developed countries are already engaged in research, development and demonstration (RD&D) of different μGrid structures from laboratory to field level. Table 1 shows that EU countries are advanced in RD&D of μGrid systems. EU energy policy also focuses on creating a competitive single market, producing energy from renewable sources and reducing the use of imported fossil fuels. Thus μGridcan improve the energy efficiency with the aim of reducing energy dependency and decarbonising the European economy. The EU target for 2020 is called 20-20-20 (Three Times Twenty) – (i) to improve energy efficiency by 20%, (ii) to reduce GHG emission by 20% and (iii) to consume 20% of energy from renewable sources [84]. In order to achieve these objectives, a number of policies have been introduced. The most important issue is the technical requirement for connecting DGs to the distribution systems in order to maintain safety and power quality. It also includes the development of connection practices, protection schemes, ancillary services and metering. The USA and other developed countries are also concerned with similar issues. A number of policies have also been implemented to attract connection of small scale embedded generators (SSEGs) by providing financial incentives to small generators such as the exemption of transmission use of system charges and transmission loss charges, climate change levy exemption, and Renewable Obligation as in the UK [85].

IEEE standard 1547-family has introduced a set of standards for interconnecting Distributed Recourses (DR) with Electric Power Systems (EPS). These are;

1. 1547.1 (2005): The rules governing connection of the DGs to the EPS.
2. 1547.2 (2008): Application guide for IEEE standard 1547.
3. 1547.3 (2007): Guide for monitoring and communication of DGs. It also facilitates interoperability of DGs in interconnected mode.
4. 1547.4 (2011): Design operation of and integration of DR island systems. Part of 1547.4 standard is considered as one of the fundamental standards as it deals with vital planning and operation aspects of μGrid, such as impacts of voltage, frequency, power quality, protection schemes and modification.
5. 1547.6 (2011): Guide of interconnection with Distribution Secondary Networks types of area EPS with DG.
6. 1547.7 (2013): This guide is a very significant step to standardize and universalize μGrid and DG systems. It emphasises on the methodology, testing steps and aspects to assess the impact of a DG on the system.

Although sustainability of μGrid depends on the geographical location, cost of energy production, technical viability and government policy in the energy market; some standards and policies towards the implementation of μGrid in the future smart grid are required. A number of the common and most important points for standards and policy development are discussed below.

Table 6
Different communication systems applicable in μGrids [83].

Technology	Spectrum	Data rate	Coverage range	Applications	Limitations
GSM	900–1800 MHz	Up to 14.4 Kpbs	1–10 km	AMI Demand Response, HAN	Low data rates
GPRS	900–1800 MHz	Up to 170 Kpbs	1–10 km	AMI Demand Response, HAN	Low data rates
3G	1.92–1.98 GHz 2.11–2.17 GHz	384 kbps to 2 Mbps	1–10 km	AMI Demand Response, HAN	Costly spectrum fees
WiMax	2.5, 3.5, 5.8 GHz	Upto 75 Mbps	10–50 km (LOS) 1–5 km (NLOS)	AMI Demand Response, HAN	Not wide spread
PLC	1–30 MHz	2–3 Mbps	1–3 km	AMI, Fraud Detection	Harsh, noisy channel env
Zig Bee	2.4 GHz-868-915 MHz	250 kbps	30–50 m	AMI, HAN	Low data rate, short range

4.1. Interconnection

Interconnection practices aim to ensure that DG system will not disturb other users of the network during normal operation, and that safety will not be jeopardized in the case of abnormal conditions. To this end, interconnection procedure typically includes technical provisions as follows:

- Voltage regulation and power quality, including steady state voltage deviations, fast variations, flicker, harmonics, DC injection.
- Protection and anti-islanding schemes
- Earthing or grounding arrangements.

The progress and problems in μGrid protection schemes are already discussed in [86]. IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems (EPS) describes the technical rules for interconnection [87]. Fig. 6 shows the recommended interconnections between the DG system and EPS. Besides this, safety and protection issues related to μGrid are also defined in IEEE Std 1547.4-2011 [88]. Policy that is required for interconnection to implement in EU, Japan and USA has been discussed in [89]. This interconnection issue has been defined as P1 in the common policy standard section below and identified in which test-beds have focused in this policy. Examples 1, 2, 5 in Table 1 have discussed this matter.

4.2. Power quality and reliability

Power quality issues and standards for electrical distribution network are mainly defined in IEC 61000-4-30 and EN 50160 [91]. Besides this, the active and reactive power control, intentional islanding, load power quality, EPS power quality, voltage regulation, frequency regulation and ride through capability and policy standards for isolated and grid-connected μGrid are described in IEEE Std 1547.4-2011 [88]. After an intentional islanding operation, DG island systems suffer adverse power quality problems such as voltage distortion. A number of small widely dispersed customer loads can cause harmonics at the power line. At the same time sensitive equipment being used by customers may be effected by the harmonics. Load imbalance produces imbalanced phase voltage and can cause excessive heat to three phase devices such as motors. While DG is working in parallel with the area EPS, the DG equipment needs to meet the power quality standards according to IEEE Std. 1547-2003 [92]. This issue is defined as P2 in the common policy section and examples 1, 2, 6 in Table 1 have focused on this issue.

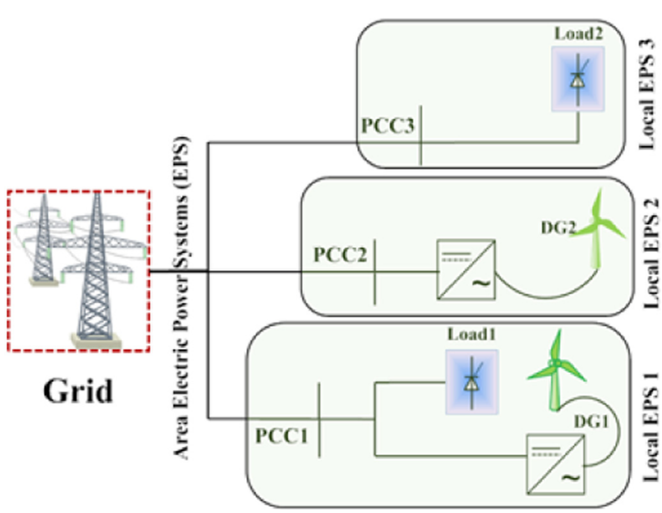

Fig. 6. Recommended interconnection between the DG sources, load and EPS [90].

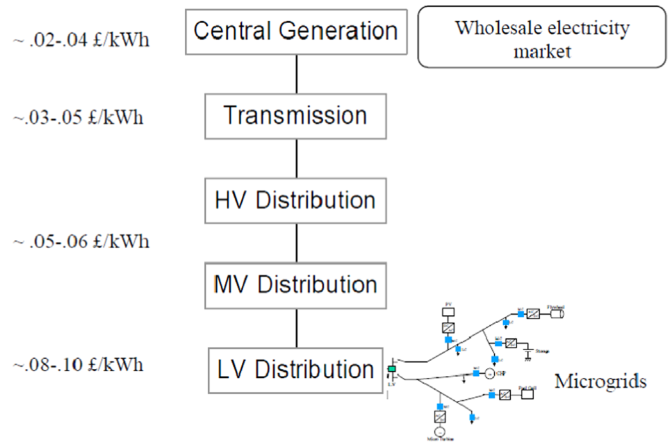

Fig. 7. Price of electricity in UK energy market [93].

4.3. Economics

In the centralized system, the cost of energy production to energy distribution differs significantly. As an example, the electricity produced by large central generation is being sold in UK wholesale markets for around 0.02–0.04 £/kWh, but by the time this electricity reaches the end consumer it is being sold at a retail price of 0.08–0.10 £/kWh which is shown as a flowchart in Fig. 7 [93]. This increase in value is driven by the added cost of transmission and distribution services to transport electricity from the point of production to consumption. At the same time, it increases the loss of energy which is also added as an extra cost for the consumer. Despite its critical effect on economics, this point is often overlooked in discussions of the relative efficiency and cost of small versus large scale generation. The practical limitations on the possible beneficial application of renewable sources are the high initial cost and the low power density. Therefore, economical viability studies of μGrid systems are very important. This issue is identified as P3 and only a few of the examples such as 29, 32 and 43 in Table 1 have discussed this point. More emphasis should be given to this matter.

The methodologies to evaluate and quantify the environmental economics-related benefits of μGrid and μGen systems are found in [93,94]. The policies to encourage integrating renewable energy based DG systems are set as:

- Exemption from transmission and losses charges.
- Climate Change Levy exemption for renewable energy.
- Renewable obligation.
- Cost reflective charging methodology for pricing of distribution networks.
- GHG emission reduction charge.

4.4. Participation in energy market

Techno-economic sustainability of a μGrid depends on its participation policy in the energy market. Currently there are two basic types of policies applied to participants in the energy market [95];

(1) The Microgrid Central Controller (μGCC) aims to serve the total demand of the μGrid, using its local production, as much as possible, without exporting power to the upstream distribution grid. For the overall distribution grid operation, such

behaviour is beneficial, because at the time of peak demand, when energy prices in the open market are high, the μGrid relieves possible network congestion by partly or fully supplying its energy needs. From the consumers' point of view, μGCC minimizes the operational cost of the μGrid, taking into account open market prices, demand, and DG bids. Thus the consumers of the μGrid share the benefits of reduced operational costs.

(2) In this case, μGrid participates in the open market, buying and selling active and reactive power to the grid, probably via an aggregator or similar energy service provider. According to this policy, the μGCC tries to maximize the value of the μGrid, i.e., maximize the corresponding revenues of the aggregator, by exchanging power with the grid. The consumers are charged for their active and reactive power consumption at the open market prices. The μGrid behaves as a single generator capable of relieving possible network congestions not only in the μGrid itself, but also by transferring energy to nearby feeders of the distribution network. This point is defined as P4 and examples of 6, 12 and 22 in Table 1 have highlighted this matter.

A comparative group of policies oriented to μGrid development in certain countries are also discussed in [96]. Considering these policies and based on the study on these existing test-beds (discussed in this paper) and the relevant policies, some common goals and policy indicators are given below. Common goals for introducing μGrid systems are:

- G1. More penetration of renewable sources to the existing grid leading to a smart grid.
- G2. Reducing the main grid transmission and distribution costs.
- G3. Reducing the GHG emissions and leading to environmental benefits.
- G4. Improving the energy security and stability.
- G5. Smart communication/control for both load management and generation systems.
- G6. Maximizing operational efficiency.
- G7. μGrid dispatchability/storage integration.

Some of the common standards and policies should be considered in general are:

P1) Interconnection

a) Protection and anti-islanding schemes
b) Earthing or grounding arrangements
c) Re-connection to the power system

P2) Power quality and reliability
P3) Economics
P4) Participation in energy market
P5) Less CO2 emission/low carbon/zero carbon policy

5. Findings

In the review of μGrid architectures, it was found that most of the test-beds are line frequency, AC μGrid. As the grid and most of the loads are AC, AC μGrid is easy to integrate with the grid. Maintaining the power quality is one of the critical tasks in AC systems. HFAC μGrid is a new concept and is a possible way for integrating renewable energy sources to the μGrid. One of the main advantages is that, PQ problems are reduced in this system. The main problems of the HFAC μGrid system is the complexity of the control devices, large voltage drop and higher long distance power loss which limits its practical implementation, but remains a topic for research. On the other hand, the main advantage in DC systems is, there are few power quality problems and therefore fewer additional control or components are required. The application of DC μGrid is very limited due to the unavailability of DC loads. But in recent years research emphasis has been given in DC μGrid system. These papers present different research aspects on DC μGrid system [97–100]. Now a day hybrid (combined AC and DC) μGrid system is also a point of interest to the μGrid researchers. Different aspects of AC DC hybrid μGrid systems have been discussed in [101,102].

Most commonly used DG sources in μGrid systems are solar PV, wind, micro-hydro and diesel. Considering the environmental benefits and reducing GHG emission, RESs are popular as DG units in Europe. America prefers wind and diesel, whilst Asia is utilizing natural gas.

Power Quality is a potential issue in μGrid systems. As the renewable DG sources are highly dependent on the environment; variability of the resource introduces some PQ problems. Power electronics converters, to interface the DG sources to the grid, introduce additional harmonics to the grid also. Hence consideration of PQ performance for any μGrid system is essential. Review of the test-beds show that very few μGrid test-beds have implemented power quality devices. Recent research on μGrid control and power quality improvement [103,104] also show that control of the DG inverters and μGrid central controller become more complex to improve the power quality and reliability. In this aspect, integration of custom power devices like Active Power Filter and Unified Power Quality Conditioner in grid connected/autonomous μGrid system is getting more importance to reduce the control complexity and improve the power quality [105,106]. Therefore, further research and implementation of more test-bed with custom power devices are required to improve their PQ and reliability and thus increase the performance of μGrid systems.

Storage system is one of the important options that a μGrid should have for its efficient and stable operation. Most of the existing test-beds have battery storage. Some have capacitor banks and flywheels as storage devices. Some of the μGrids have a combination of two or three storage units together and some do not have any storage units at all. From the review it was found that in most cases (except two), if there is no storage device, at least one controllable DG source such as diesel or natural gas is present in the system. If the system does not have any storage device and only RESs are present, then grid integration is a very important factor for that μGrid system.

Policies for μGrid systems are not yet well defined. From Table 1, it has been identified that in terms of existing prominent μGrids, EU countries are in the leading position. In most μGrid systems some of the common goals and policies are found such as more penetration of RE sources (as a hybrid system) to the existing grid, reduced main grid transmission and distribution cost, reducing GHG emission, smart communication/control, improved energy security and reliability. Very few systems deal with the interconnection (anti-islanding schemes, earthing, and reconnection), power quality and reliability, economics, participation in energy market and low/zero carbon policy for their policy development. USA also focuses on these agendas including maximum operational efficiency and μGrid dispatchability. μGrids in Asia has not yet penetrated to any significant extent in energy markets.

6. Conclusion and future trends

DC μGrid is not yet very popular in the European region although they have advantages with fewer PQ problems. More emphasis should be given to their development. The main barrier to expand this technology is the low number of DC loads. As technology has advanced, more DC compatible loads will be introduced. Most of the existing AC μGrid test beds have included batteries as storage devices although they are expensive and further technological improvement can help to make them become economically viable.

More penetration of RES is expected in μGrid systems as they are almost pollution-free and thus environment friendly. In that case, further efforts should be made to solve the PQ problems associated with RE sources and grid stability.

A combination of different RE systems together with storage has the significant potential as such a system helps to store clean energy whenever available. As most of the μGrids are close to the grid and integration is possible, it would be beneficial to have some experimentation and performance analysis on μG with fully renewable sources.

The advancement in storage and battery systems is promising in terms of cost and technology. Although their initial system cost and operation and maintenance costs (O&M) may be higher, the requirement of demand side management and maximizing the use of available RESs, μGrid with storage devices could be viable options in the near future.

All the existing test beds described have limited technical information but generally no economical information is available. In terms of techno-economic benefits, the systems should be optimized both technically and economically. Reducing the number of system components, reducing the installation and management costs, improving the system integrity, improving source and load efficiency, and introduction of source or demand side management can enhance the viability of any system. Reducing conventional sources is required to achieve environmental benefits. Therefore, moving towards the operation of AC or DC and a hybrid μGrid consisting of fully renewable sources with reduced storage and integration with grid may be the better candidate for future μGrid implementations.

Communication systems are all pervasive and the energy required for such communication system is reducing by implementing energy efficient and low cost wireless sensor networks. Load management and control of μGrid system now becomes more efficient. These issues indicate that present μGrid research and development are concerned with the gradual move towards the smart grid concept.

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