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Microgrid testbeds around the world: State of art

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ABSTRACT

This paper deals with the recent evolution of microgrids being used around the world in real life applications as well as laboratory application for research. This study is intended to introduce the subject by reviewing the components level, structure and types of microgrid applications installed as a plant or modeled as a simulation environment. The paper also presents a survey regarding published papers on why the microgrid is required, and what the components and control systems are which constitute the actual microgrid studies. It leads the researcher to see the microgrid in terms of the actual bigger picture of today and creates a new outlook about the potential developments. Additionally, comparison of microgrids in various regions based on several parameters allows researchers to define the required criteria and features of a special microgrid that is chosen for a particular scenario. The authors of this paper also tabulated all the necessary information about microgrids, and proposed a standard microgrid for better power quality and optimizing energy generation. Consequently, it is focused on inadequate knowledge and technology gaps in the power system field with regards to the future, and it is this which has been illustrated for the reader.

The existing microgrid testbeds all around the world have been studied and analyzed and several of them are explained as an example in this study. Later, those investigated distribution systems are classified based on region (North America, Europe and Asia) and, as presented in literature, a significant amount of deviation has been found. Several tabulated data sheets have been used to compare and contrast the existing test systems. This research has been concluded with worthy findings and potential areas of research that would enhance the current distributed network as well as introduce microgrid testbeds comprehensively, and aid designers in optimizing green distributed system efficiency for a reliable power supply.

1. Introduction

The definition of the microgrid is "a localized group of electricity sources and loads that it normally operates connected to, that acts as a single controllable entity and in a synchronized way with the conventional utility grid, but can be disconnected and independently operated according to physical and/or economic conditions" [1]. The microgrid consists of numerous autonomously power-generating sources that constitute a flexible and efficient infrastructure [2]. From this perspective, even though some of the generators fail to produce electricity, it does not change the reality that the entire generation system is a microgrid. The excess power of a distributed system is evaluated by selling to the utility grid, or it can be stored in a storage system. The peak power of the microgrid can range from a few kilowatts to megawatts. There are several features of the typical microgrid, such as seamless transition to/from utility, integration of renewable assets to support loads without utility presence and high level of automation.

The availability and cost of fossil fuel, power quality and stability issues, reliability of power supply due to unplanned grown up sources and loads, and natural disasters, unavailability of modern control facilities, aging infrastructure, mass electrification, climate change and many other problems have been faced by today's power system industry. One of the most practical solutions for green and reliable power is the microgrid. It has served the three main goals of society, those being reliability (both physical and cyber), sustainability, and economic efficiency. There are several factors why we need distributed generation systems, such as [3–6]

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i. If every user (building/company/hospital/market) thinks about reliable power and keeps own generation/battery/diesel engine as a backup, then that is the most expensive power system. In a microgrid system, we can get rid of those backup systems because the user does not have to think of the feeding load during a critical time.
ii. We can save a billion dollars if we can manage a few hundred summer peak hours by shifting or eliminating loads.
iii. So, reliability is a very good justification for selling microgrids. It could also be justified for economic reasons (i.e. Western US). For sustainability, there is not much to compel users in the US, but there is in China, where environmental issues are very important.
iv. Microgrids could solve the energy crisis. It is "energy security" to the power industry.
v. Transmission losses get highly reduced.
vi. The microgrid allows one to decrease overall costs and emissions without requiring any change in daily lifestyles.
vii. Critical loads can be supplied in a reliable and highly efficient way by microgrids
viii. In light of increasing cyber threats, it solves the cyber security problem.
ix. Viable for regions with underdeveloped transmission infrastructures, for example remote villages, islands

The design of electrical power distribution systems has been classified in three ways: Radial distribution system, Mesh/Loop distribution system, and Network distribution system. The pros and cons of the distribution systems are important to know in order to comment on microgrid applications and source varieties. In practice, the common application is done with a combination of those three systems. Although it is the most inexpensive distribution system to construct, the radial system is extensively issued in populated areas. It involves just one power source for a cluster of clients as shown in Fig. 1. Since all the consumers are connected to a unified source, any failure which occurs in the power line will cause a blackout [7,8].

The mesh system, as an alternative to the radial, creates a distribution system that crosses all over the consumer area and ends at the generation sight. By placing switch breakers in proper sections, the power can be supplied to the consumers in a bidirectional structure. In case of any fault occurring in one of the generators, the breakers are automatically switched and the power flow is sustained by service. This opportunity makes the mesh better than the radial system for microgrid applications. During power failures which occur due to a line fault, the utility should find the defective area and switch around it to restore facility with a minimum number of consumer interruptions. Since the mesh system requires additional switches, conductors, and breakers, it is more expensive to construct compared to the radial. However, it provides more robust distribution systems [9–11].

Network systems are the most sophisticated and interlocking mesh systems. Any consumer can be supplied from few power supplies and it surely adds a huge advantage in terms of reliability. This system is typically used only in crowded, high power requiring municipal or downtown areas because of excessive expenses. In current microgrid research, it is found that mostly either radial or mesh distribution systems are used [12–16].

Researchers all over the world are making huge efforts to study microgrids and to construct testbeds and demonstration sites, while the classification of microgrids and relevant key technologies need to be addressed. In this paper, we divide microgrids into three types: facility microgrids, remote microgrids, and utility microgrids, based on their respective integration levels into the power utility grid, impact on main utility, their different responsibilities, application areas and relevant key technologies, as shown in Table 1. Facility microgrid and utility microgrids have utility connections modes but remote microgrids do not have that choice. The remote microgrids span geographically a larger area compared to the facility and utility microgrids. The plant microgrid can pursue the operation in a planned or an unplanned island mode and the sources, loads, network parameters, and control topologies vary in each and every microgrid. The classification of microgrid based on application has also been visualized in Fig. 2, where percentages of microgrid application and capacity for 2012 are shown [17–19,25]. Moreover, a detailed study of various microgrid types has been illustrated in Table 1.

2. Distribution system

Three different type of distribution networks exist.

(a) Direct current line.
(b) 60/50 Hz alternative current line frequency.
(c) High frequency alternating current (HFAC) [7,20].

Distributed energy resources typically produce a direct current which is insignificant concerning power quality; that is why research has placed more stress on the DC distribution system [4,21,22]. However, most of the loads are operated in an AC system; therefore, DC distribution systems may not be popular so far. Microgrids are generally line frequency utility grids. The DERs are connected in a common bus in the microgrid. Prior to the use of DC current being in demand from DERs, a conversion is required to make it AC supply by using an electronic power inverter.

Using a HFAC transmission line in a microgrid is a novel concept that is still at the developing phase. In a HFAC microgrid, the DERs are coupled to a common bus. The electronic power devices convert the frequency of the generated electricity to 500/1000 Hz AC and transmit to the load side where it is again converted to 50/60 Hz AC by using an AC/AC converter [23,24]. The load is connected to the distribution line, which can assure an effective interaction between the microgrid and distribution network. The higher ordered harmonics can be easily filtered at the higher frequency, and the PQ problems are solved this way. However, power loss increases due to the increase of line reactance are one of the main drawbacks of HFAC [25].

Fig. 1. Electrical power distribution system.

Table 1
Detail classification of microgrid.

Classification of Microgrid								
Classification	Integrated level	Utilities' impact	Responsibility	Application area	Operational mode	Geographically span	Power quality	Remarks
Facility microgrid	Middle level	Little impact on utilities	For complement mostly for vital systems	Mainly found in North America specially for Industry/Institution application where technology is matured	Intentional or unintentional island mode	2 miles	High	Making great use of renewable energy, increasing energy efficiency, reducing pollution, greenhouse gas emissions & high power quality reliability for sensitive loads as well to single business-entity
Remote microgrid	Low level	No impact on utilities	Independent system for isolated electrification	Mainly found in distant areas, Islands, developing countries	Islanded Mode only	30 miles	Relaxed	Mostly decentralized control & maximum power use is limited for the customers
Utility microgrid	High level	Massive impact on utilities	For support of power systems	Mainly found in Japan, Europe, China where renewable energy is rapidly developing	Grid tie mode	15 miles	Medium	Providing high power quality & reliability to sensitive local loads, contributing to utility stability & robustness as well

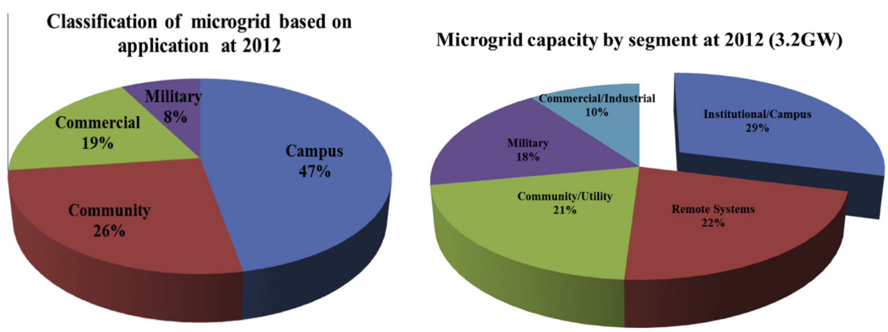

Fig. 2. Classification of microgrid.

2.1. Distributed generation technology

Several types of distributed generation technologies have been used in microgrid systems. Some of them are renewable and the rest is fossil distributed generation. A complete study on DG technology has been given in Table 2 and Table 3. From the tables researchers can figure out which technology should be used for their design system and why they ought to pick up those technologies. With the help of tabulated sheets we can also analyze our design system performance as well as perform a cost–benefit analysis. Hence, the maximum efficiency can be extracted with the possibility of generating entirely green energy. Putting green energy into power will reduce our environmental hazards, and offers a reliable power source for the community.

2.2. AC microgrid systems

The majority of the electric loads since last century have been operated with AC power. So, the standard choice for commercial power systems is ultimately an AC distribution system [16,26]. The long-distance capability of AC power, its ability to easily transform into various levels of output for different applications, and its natural characteristic inherited from the fossil fuel driven rotating machine, give AC power network superiority. Nowadays, researchers have focused on renewable-based distribution systems and various communities have implemented it; additionally a huge study has been going on since last decade on operating feasibility. Commonly, an AC microgrid system is connected with a medium voltage distribution line at the point of PCC. The distributed generations, storage devices and loads are attached with a common bus base at the distribution networks. During the grid-tied mode, the system voltage and frequency are maintained by utility grids while energy storage devices, non-renewable DGs and adjustable loads with control techniques help to keep standard voltage and frequency level during islanded mode.

Disadvantages of the AC microgrid:

- Each distributed generation and utility grid couple has to be synchronized for the AC microgrid.
- It has a huge effect on power quality; for example, inrush current is usually produced by transformers and the induction machine.
- There is concern about three phase unbalance, such as the photovoltaic system (single phase loads, single phase generators).

2.3. DC microgrid systems

In a DC microgrid, energy storage and a large percentage of the sources and the loads are interconnected through one or more DC busses. Nonetheless, AC buses or some sort of DC to AC converter are still necessary due to the fact that some sources and loads cannot be directly connected to DC [27–29]. Furthermore, as long as AC is going to be used for distribution, the DC microgrid will at some point be connected to the AC grid. Hence, it is suggested that in DC microgrids along with AC buses, they should be considered as two parts of a mixed AC/DC microgrid, which is coupled to the AC grid through the point of PCC.

Advantages of the DC microgrid:

- Facilitates DC loads to operate with "native" power as most modern devices need DC power input.
- Synchronization of distributed generators is not required.
- Ability to use distributed renewable energy sources that naturally generate DC, for example PV or wind.
- The ability to use Class 2 NEC (National Electric Code) loads at non-lethal voltages (e.g. 24 V).
- No power factor losses because a DC system has zero frequency.
- In a DC microgrid, loads are free from voltage distortion, like voltage sag, unbalanced voltage, or voltage harmonics [27].
- No inverter or transformer losses because those devices are not applicable in a DC system.
- DC–DC switching regulators can reach high efficiencies if it is necessary for certain loads.
- Higher efficiency than AC microgrids due to less conversion loss also resulting in less thermal/heat wastage, and fewer components as well compared to AC systems.

In contrast, there are several down sides to implementing the DC microgrid in our present power system. A DC distribution network needs to be built in order to implement a DC microgrid. Moreover, due to the absence of a zero crossing point, it is hard to design a protection system for DC microgrid networks compared to AC microgrid systems. Generally, high system efficiency is required for operating DC microgrid loads [15,28].

2.4. Comparison of AC and DC microgrids

Looking back at a century when the great effect of electricity was seen in the industry, a great competition took place with regards to power, AC or DC, known as the "War of the Currents." The few important points of the argument that serve our purposes are: (1) the power generation cost in single large plants was cheaper than the cost of many distributed ones; (2) AC could travel long distances with low losses, unlike DC; (3) radiant lamps were the majority of the load and they operated on AC or DC; and (4) semi-conductors had not yet been invented. However, now, with the invention of Choppers and Boosters it is feasible to change the level of DC voltages for different applications. Besides, power industries can mostly escape commutation problems, plus it can be replaced by a rectifier.

The DC microgrid only requires voltage stabilization, while an AC grid involves almost all the waveforms and should be controlled. The DC microgrids are mostly installed by using solar panels that enable one to make a connection to a utility grid over a single string inverter. On the other hand, AC microgrids require more than one inverter to be connected to the grid. The absence of electromagnetic interference, and easy power transfer at PCC are also assumed to be advantages of DC microgrid compared to AC. Despite these advantages of the DC microgrid, AC systems provide several advantages in transmission segments regarding its transformer and breaker-based control infrastructure, whereas the DC microgrid has more advantages in terms of converter control and efficiency in distribution segments [29–31]. A detailed study on AC distribution networks and DC distribution networks has been illustrated in Table 4.

The majority of installed microgrids for experimental and operational purposes have used AC distribution networks. AC voltage can be increased and can be decreased easily by using electrical transformers. In contrast, a significantly complex and costly DC–DC converter is required for different levels of DC voltage supplied for different applications [15]. Besides, the protection system of DC distribution is not mature enough compared to the AC system and more research is needed prior to implementing such a protection system. The suitable application of low voltage DC microgrids is for sensitive electronic loads, telecommunication power devices, and control and protection of power systems. Since the existence of DC microgrids is still limited and technology has not matured enough, researchers are showing more interest in the DC microgrid as a future reliable power system.

Recent trends for selecting the nature of power for distributed power systems [17,43,44]:

- Today's power industry is composed of numerous inverter-based loads and the conversion of AC–DC, DC–DC and DC–AC is required.
- The renewable distribution generation naturally has DC power output, for example: photovoltaic, fuel cell, variable speed wind turbine, micro-turbine, etc.
- Recently, several microgrids have been installed with DC-couples.
- Power quality requirements are also another important aspect.
- DC microgrids/nanogrids have an effect on the selection of the nature of power and DC distributed power systems (DPS) as well.
- Some applications inherently require DC power, for example: telecommunication systems, DC-link for UPS systems, and several isolated systems too, such as avionic, automotive, and marine.

3. Microgrid testbeds around the world

Numerous microgrids have been implemented and are functioning to supply power, or have been installed at the laboratory level to conduct research all over the world to analyze the operation of microgrids in detail. Most of the experiments that are run by scientists are related to islanded or grid-tied systems to support communities. Since the new concept of the microgrid is very versatile, the experiment conditions, usages, and the objectives have widely varied [4,16,32,33].

3.1. Microgrid project in North America region

The Consortium for Electric Reliability Technology Solutions (CERTS) is the most renowned of U.S. microgrids. The main aim of this project was to make it easier to operate the micro-generators together to feed the utility grid. As a result, three advanced concepts given below have been developed to decrease the field engineering work on microgrids [4].

- Ensure automatic and transition between grid connected and islanded modes.
- A protection method inside the microgrid during faults.
- A microgrid control scheme to stabilize system frequency and voltage without communication system.

Moreover, the Georgia Institute of Technology and the Distributed Energy Resources Customer Adoption Model DER-CAM at the Berkeley Lab have simulated several software tools, for example, a microgrid analysis tool for microgrid systems. Typically, the project has decentralized control with some sort of storage system as shown in Table 5. The majority of distribution systems are presently at the research and development (R&D) stage and the goal was to implement policies for various microgrid types in terms of control and protection. North America is not only focused on renewable energy generation but also focused on sustaining the reliability of power sources by integrating microgrid technology. Furthermore, it is focusing on the use of decentralized control for the regulation of distribution level voltage and frequency. A comprehensive study on North American microgrids has been done

Table 2
Summary of distributed technology.

Summary of distributed generation technologies													
Fossil								Renewable					
Technology	Small steam turbines	Gas turbines	Micro-turbines	Reciprocating internal combustion engines	Stirling engines	Fuel cells-high temperature	Fuel cells-low temperature	PV	Small hydro	Wind onshore	Wind offshore	Geothermal	Solar thermal
Basics													
Type of fuel	Gas, coal, biomass	Gas turbines	gas	Diesel, oil, biofuel, gas	Gas, solar	Gas, hydrogen	Gas, hydrogen	Solar	Water	Wind onshore	Wind	Earth	Earth
Capacity range (MW)	0.5–10+	0.5–10+	0.03–0.5	0.5–10+	<0.01–1+	1–10+	<0.1–3+	<0.001–5	0.05–1	0.5–6+	5–10+	0.5–3+	0.001–2
Status	Commercial	Commercial	Developing/ Commercial	Developing/ demo/ commercial	Developing/ commercial	Developing/ commercial	commercial	commercial	Developing/ commercial	Commercial	Developing/ commercial	Developing/ demo/ commercial	Developing/ demo/ commercial
Pure economics	Cheap	Cheap	Moderate	Cheap/ Absolutely environmentally friendly	Moderate/ Expensive technology	Expensive technology	Expensive technology	Expensive technology	Moderate	Moderate	Expensive technology	Moderate/ Expensive technology	Moderate
Environmental features	Poorly/ Moderately	Poorly/ Moderately	Moderately	Poorly	Moderately	Moderately/ Absolutely environmentally friendly	Moderately/ Absolutely environmentally friendly	Absolutely environmentally friendly	Absolutely environ mentally friendly	Absolutely environ mentally friendly	Absolutely environ mentally friendly	Absolutely environ mentally friendly	Absolutely environ mentally friendly
Social motivation	Low	Medium	Medium	Low	Medium/High	High	High	High	High	High	High	Medium	High
Actual deployment	High	High	Small, increasing	High	Small	Small	Small, increasing	Small, rapidly increasing	Medium	Medium	Small, rapidly increasing	Small	Small
Application													
Industrial	Perfectly match to the requirements of the sector	Perfectly match to the requirements of the sector	Usable	Perfectly match to the requirements of the sector	Usable	Perfectly match to the requirements of the sector	Suggested	Usable	Suggested	Suggested	Not suggested	Not suggested	Not suggested
Commercial	Usable	Suggested	Suggested	Perfectly match to the requirements of the sector	Perfectly match to the requirements of the sector	Usable	Perfectly match to the requirements of the sector	Suggested	Usable	Usable	Not suggested	Not suggested	Not suggested
Residential	Not suggested	Not suggested	Perfectly match to the requirements of the sector	Suggested	Suggested/ Perfectly match to the requirements of the sector	Not suggested	Perfectly match to the requirements of the sector	Perfectly match to the requirements of the sector	Not suggested	Not suggested	Not suggested	Not suggested	Not suggested
Costs													
Is CHP possible?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes
Capital costs (Euro/Kw)	550–1250	500–1100	1000–200	350–1000	1500–8000	3500–10000	2000–8000	4000–8000	1400–5000	800–2000	1200–3000	800–400	1500–2000
Installation (Euro/kW)	100–200	65–150	50–200	60–120	40–200	500–850	500–850	40–150	100–200	100–200	600–800	200–400	100–200
Electricity generating costs(Euroct/kW h)	3–7	3–5	8–15	4–7	9–15	15–35	10–25	20–40	6–14	6–10	8–15	NA	NA
Expected life-time	20	20	20	20	15	10	10	20	60	20	20	20	20

Table 3
Review of distributed technology.

DGs technologies review					
Technology	Recip engine: diesel	Recip engine: NG	Microturbine	Combustion gas turbine	Fuel cell
Size	30 kW–6+ MW	30 kW–6+ MW	30–400 kW	0.5–30+ MW	100–3000 kW
Installed Cost ($/kW)	600–1000	700–1200	1200–1700	400–900	4000–5000
Electrical Efficiency (LHV)	30–43%	30–42%	14–30%	21–40%	36–50%
Overall Efficiency	~80–85%	~80–85%	~80–85%	~80–90%	~80–85%
Total Maintenance Costs3 ($/kWh)	0.005–0.015	0.007–0.020	0.008–0.015	0.004–0.010	0.0019–0.0153
Footprint (sqft/kW)	0.22–0.31	0.28–0.37	0.15–0.35	0.02–0.61	0.9
Emissions (gm/bhp-hr unless otherwise noted)	NOx: 7–9 CO: 0.3–0.7	NOx: 0.7–13 CO: 1–2	NOx: 9–50 ppm CO: 9–50 ppm	NOx: <9–50 ppm CO: <15–50 ppm	NOx: <0.02 CO: <0.01

http://www.distributed-generation.com/technologies.htm.

Table 4
Summary on AC distribution network and DC distribution network.

Impact factors	AC distribution system	DC distribution system
Transmission of power over short distant	There is a significant power loss in line hence AC system is less efficacy More number of conductors requires for specific amount of power transmission [12]	It has better efficiency hence good for power transmission for short distant Less number of conductors requires for specific amount of power transmission
Stability and synchronization	External disturbances effect on stability, real & reactive power can manage microgrid stability independently & synchronization between DGs and utility grid is required [23,45]	DC distribution system is free from stability and synchronization problem where the voltage sag is directly consequences of real power flow over power line
Reluctance	Reluctance is present in AC line	DC line is free from reluctance thus capable to transmit more power
Frequency (50 Hz or 60 Hz)/health concerns	Monitoring of AC system is required as it is fluctuated continually Line inductance and switching introduces transient stability concern Electromagnetic interference produces health concern	Frequency monitoring is needless as DC has zero frequency Absent of transient stability concern There is no electromagnetic phenomena is DC system to produce health concern
Resistance	In AC system, the line resistance is high	It has minimum line resistance
Susceptance	A huge concern of charging current and over-voltage problem	Those problems do not exist in DC system
Analysis	The analysis of AC system require dealing with complex number, hence it is tough	DS system analysis has only real numbers i.e. simpler
HVDC transmission	It is suitable for HVDC transmission	It is not suitable for HVDC transmission
Long distant power transmission ability	AC power can be transmitted over long distances	Inappropriate of this application
Reactive power	Need to monitor reactive power continuously	Reactive power is absent in DC system
Skin effect	Need bigger cross sectional area conductor due to skin effect	No skin effect on DC system so small cross sectional area conductor will work
Corona effect	More Corona losses on AC line [21]	There are tiny losses from Corona effect in DC line
Protection system	Simpler, cheaper and matured protection system	The protection system is complex, expensive and not matured enough
Maintenance	Maintenance is easy & inexpensive	Maintenance of AC substation hard and expensive
Transformer	Voltage level is adjustable using transformer	Transformer is not applicable in DC system
Capacitance/ Inductance effect	Power losses on lines during no load/open circuit	No capacitance/inductance effect
Telecommunication interference	AC system has telecommunication/wireless network interference	DC system has no telecommunication/wireless network interference
Efficiency	Less due to too many conversions	More due to less conversion
Noise & danger	More noisy and more danger	Less noisy and less danger
Conversion losses	DC to AC conversion loss is less	AC to DC conversion loss is more
Peak voltage	Higher (1.4 times) than nominal value	Same as nominal value
Control method	Direct Power Control in AC systems	Indirect power control in DC system
Blackout/voltage sag	During blackout/voltage sag AC system is affected	During blackout/voltage sag DC system is unaffected
Variable-speed drives	It is hard to obtain variable speed control	It is easy to obtain variable speed control

and tabulated in Table 5, which aids researchers to find the necessary information for designing and analyzing a distribution system. Several examples of existing microgrid testbeds in North America are given below.

3.1.1. University of Texas at Arlington microgrid testbed

The UTA Microgrid lab comprises of three independent deputy microgrids operating in grid tied or islanded fashion. Each deputy grid has a 24 VDC bus as well as a 120VAC-60 Hz AC bus. For typical configuration, two 12 VDC lead acid batteries are coupled in series as the primary energy storage. The batteries on each grid are recharged using devoted solar panels and wind turbines, or a PEM fuel cell and DC/AC inverter (manufactured by Outback Power Systems). The programmable load is connected to each AC bus. The grid has Crydom solid-state relays mounted on the various busses which are controlled using a National Instruments Compact RIO control system. The entire UTA grid is shown in Fig. 3. The performance of a microgrid is based on its ability to supply reliable and quality power to loads within the standards set out by defined specifications, such as MIL-STD-1399-300B or IEEE-STD-519. In each of these standards, regulations are given which specify the allowable variance in the voltage, current, and frequency. The DC microgrids mostly used for residential and static loads where the power line is used as a communication medium [3,20,34,35].

Table 5
Microgrid Testbed at North America.

Microgird Testbed at North America						
Project Name	Detail [Structure/Power Nature/Type]	DGs_Renewable	DGs_Nonrenewable	Control	Load	Storage
CERTS Testbed, Ohio	Mesh/AC/Testbed	No	Gas	Decentralized	Residential	Battery
UW Madison Testbed, Wisconsin	Radial/AC/Testbed	PV	Diesel	Decentralized	Static	Battery
University of Miami Testbed, Florida	Radial/DC/Testbed	PV, Fuel Cell	No	Decentralized	Residential	Battery
Sandia National Lab Testbed, Washington, DC	Radial/DC/Testbed	PV, Wind	Diesel	Decentralized	Residential, Static	Battery
UT Arlington Testbed, Texas	Radial/DC/Testbed	PV, Wind, Fuel Cell	Diesel, Gas	Decentralized	Residential, Static	Battery
FIU Testbed, Florida	Radial/DC/Testbed	PV, Wind, Fuel Cell	Motor	Centralized, Agent based	Residential, Motor	Flywheel
Laboratory scale microgrid testbed, New Jersey	Radial/AC/Real	PV	No	Centralized	Residential, Motor	Battery
UT Austin, Texas	Radial/AC/Testbed	No	Diesel, Gas, Motor	Decentralized	Static, Motor	Flywheel
Microgrid testbed at Albuquerque, New Mexico	Radial/AC/Real	PV, Fuel Cell, CHP	Gas	Decentralized	Residential, Commercial, Motor	Capacitor
Utility Microgrid at Los Alamos, New Mexico	Radial/AC/Real	PV	No	Decentralized	Residential	Battery
RIT Microgrid, New York	Mesh/AC/Testbed	PV, Wind, Fuel Cell	No	Decentralized	Residential, Static, Motor	No
Mad River Park Microgrid, Vermont	Mesh/AC/Testbed	PV	Diesel, Motor	Decentralized	Residential, Commercial, Industrial	Battery
Palmade Microgrid, California	Radial/AC/Real	Wind, Hydro	Diesel, Gas	Decentralized	Residential, Commercial, Static, Motor	Capacitor
Hawai Hydrogen Power Park, Hawaii	Radial/DC/Testbed	PV, Wind, Fuel Cell	No	Centralized	Residential, Static	Battery
Boston Bar-BC Hydro	Radial/AC/Real	Hydro	Diesel	Decentralized	Residential	No
Boralex Plant, Qubee	Radial/AC/Real	No	Stream	Decentralized	Residential	No
VSC feeded Microgrid, Toronto	Radial/AC/Testbed	No	Motor	Decentralized	Static, Motor, Electronics	Capacitor
Ramea wind-diesel Microgrid, NL	Mesh/AC/Real	Wind	Diesel	Decentralized	Residential	Battery
Fortis-Alberta Microgrid, Alberta	Radial/AC Real and Testbed	Wind, Hydro	No	Centralized	Industrial	No data found about storage

3.1.2. Microgrid testbed at Albuquerque, New Mexico by Shimizu Institute of Technology (SIT)

The Shimizu corporation was founded in 1804 for the purpose of power system project planning, designing and facility management and maintenance and renovation. It developed a microgrid testbed at Albuquerque around 2010. This SIT testbed consists of a gas engine generator (240 kW), fuel cell (80 kW), lead acid battery (50 kW/100 kW), PV (50 kW), Dummy load (100 kW) and electric load of 400 kW. The facility has Building Energy Management Systems (BEMS), a heat source equipment controller and a power supply equipment controller to regulate both supply and demand. This radial type distribution system serves residential and commercial loads with the help of power line communication [34]. The block diagram of the USA-Japan joint microgrid project testbed has been drawn in Fig. 4.

3.1.3. British Columbia Institute of Technology microgrid testbed at BC

The British Columbia Institute of Technology (BCIT) has designed and developed a scaled-down version of the microgrid in order to present it to utility companies and researchers. All the participants of this project can work together to develop related parts of the microgrid such as infrastructure, protocols, testbeds, and several other required experimental configurations to sustain the innovations to promote the solutions and development of microgrid technology for the North American region. The 1.2 MW microgrid was implemented at BCIT's Main Campus in Burnaby around 2009. This campus type microgrid consists of two wind turbines (5 kW each), PV modules (300 kW), thermal turbine (250 kW), Li-ion battery (550 kW h) and campus loads (EV charging stations, industrial load, classrooms & offices, residences) [2]. There was a command & control unit which comprised with the substation automation lab, MG operation control center and MG controller. A campus-wide communication network was also available in this distribution system, for example, WI-Max, ISM RF, PLC, Fiber and so on, as shown in Fig. 5.

3.2. Microgrid project in Japan region

Japan has been dedicated to generating renewable energy at an optimal level; however, this decision threatens the power quality reputation in that region. The most common renewable distributed generation in Japan is wind and photovoltaic systems, and those sources are usually of an intermittent nature which is an external impediment. Microgrids may be able to handle these problems, which has prompted the projects in Japan, including one of the most important implementation projects. The majority of the projects are sponsored by the New Energy and Industrial Technology Development Organization (NEDO) [4]. Very few projects have used non-renewable distributed generations. However, the most popular control technique is centralized control with a storage system as shown in Table 6, and an example of a typical Japanese microgrid given below as well.

3.2.1. Kyoto eco-energy microgrid testbed at Kythnos Island in Japan

The Kythnos Island microgrid project, named "Kyoto Eco-Energy," has also been supported by NEDO since around 2005.

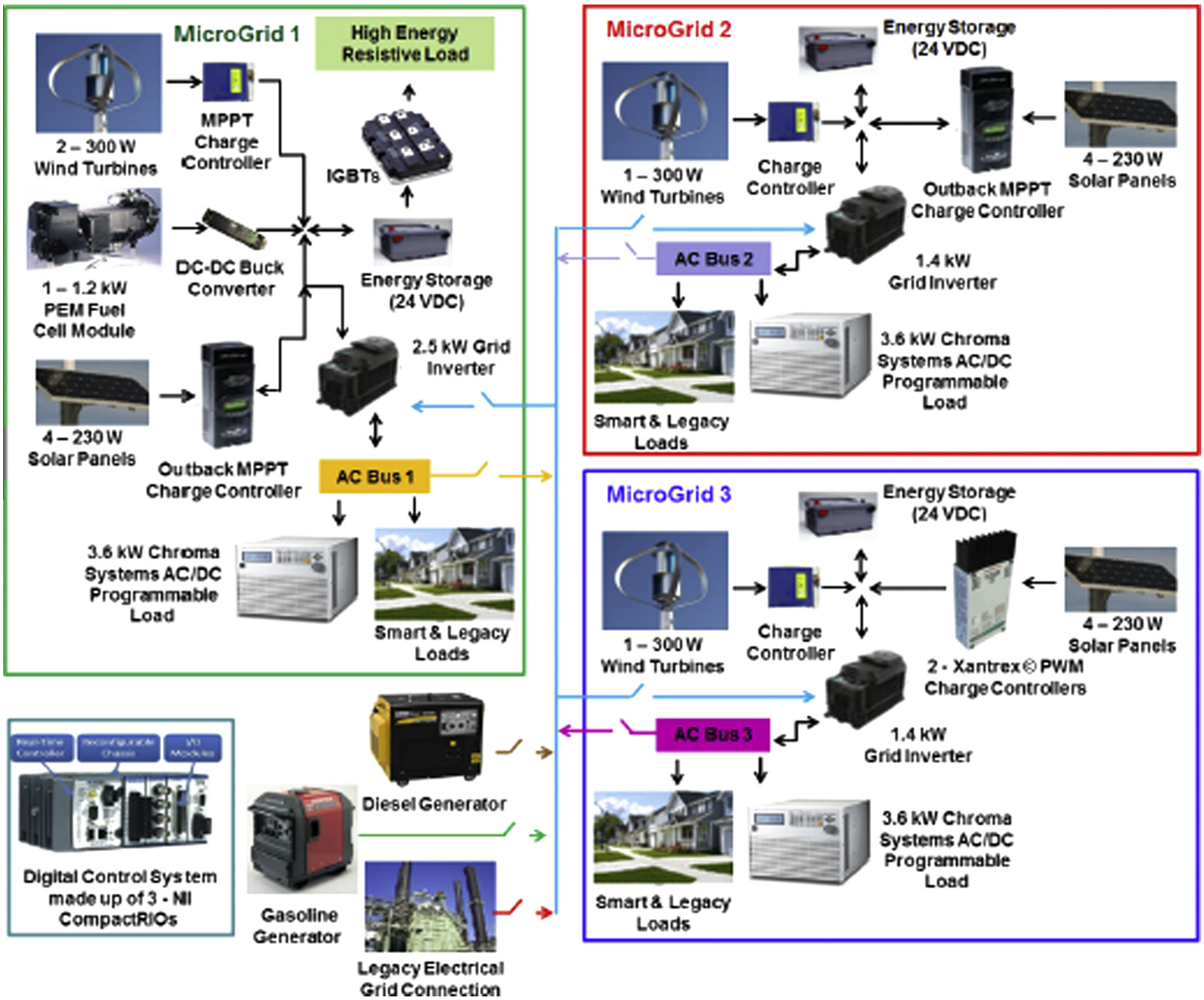

Fig. 3. UTA microgrid laboratory.

The schematic diagram of the virtual type AC microgrid has been shown in Fig. 6, where each and every distributed energy resource and load is connected to the utility grid through a substation, and a control system is used to integrate these elements. This utility supported microgrid is composed of gas engines with a capacity of 400 kW, a 250 kW MCFC and a 100 kW lead-acid battery, two photovoltaic systems and 50 kW small wind turbine. The energy demand is maintained through a microgrid and utility grid by using remote monitoring and controlling. The centralized control system and the communication system are built on several standards, such as the Integrated Services Digital Network (ISDN) or Asymmetric Digital Subscriber Line (ADSL) Internet service provider (ISP) for the Internet, which are the solitary connection choices existing in that countryside region of Japan. The mesh type Kyotango microgrid is mainly used for residential load and serves the purpose of a utility microgrid to support the existent grid [3].

3.3. Microgrid project in European Union (EU) region

The European Union has one of the highest levels of global warming and climate change awareness at present. For that reason, there are certain requirements that should be met by each member and every state within the next decade. There are numerous laws defined by the European Parliament, for example, 2001/77/EC, 2003/30/EC and 2006/32/EC. These laws specify that the amount of carbon footprint emissions will be decreased by stated amounts for every state, while increasing the amount of renewable energy generation, hence reducing fossil energy usage and the net amount of energy consumption will be compacted by increasing energy efficiency [7,42].

Consequently, there are inducements from the EU and numerous developments in progress among the states. Almost every facility in EU has used a sophisticated storage system and nonrenewable distributed generation to maintain power quality and mainly testbeds are experimenting with residential loads as shown in Table 7 with the example of the University of Seville Spain's microgrid at Seville.

3.3.1. Microgrid testbed in University of Seville Spain

The schematic diagram of the University of Seville microgrid is illustrated in Fig. 7 and this domestic distribution system is primarily powered by a photovoltaic array. The intermittent nature of solar resources has raised reliability issues; an electrolyzer is placed in the main power distribution line to overcome this problem. During excess power generation, extra electricity is used to produce and store hydrogen. In contrast, a fuel cell generates

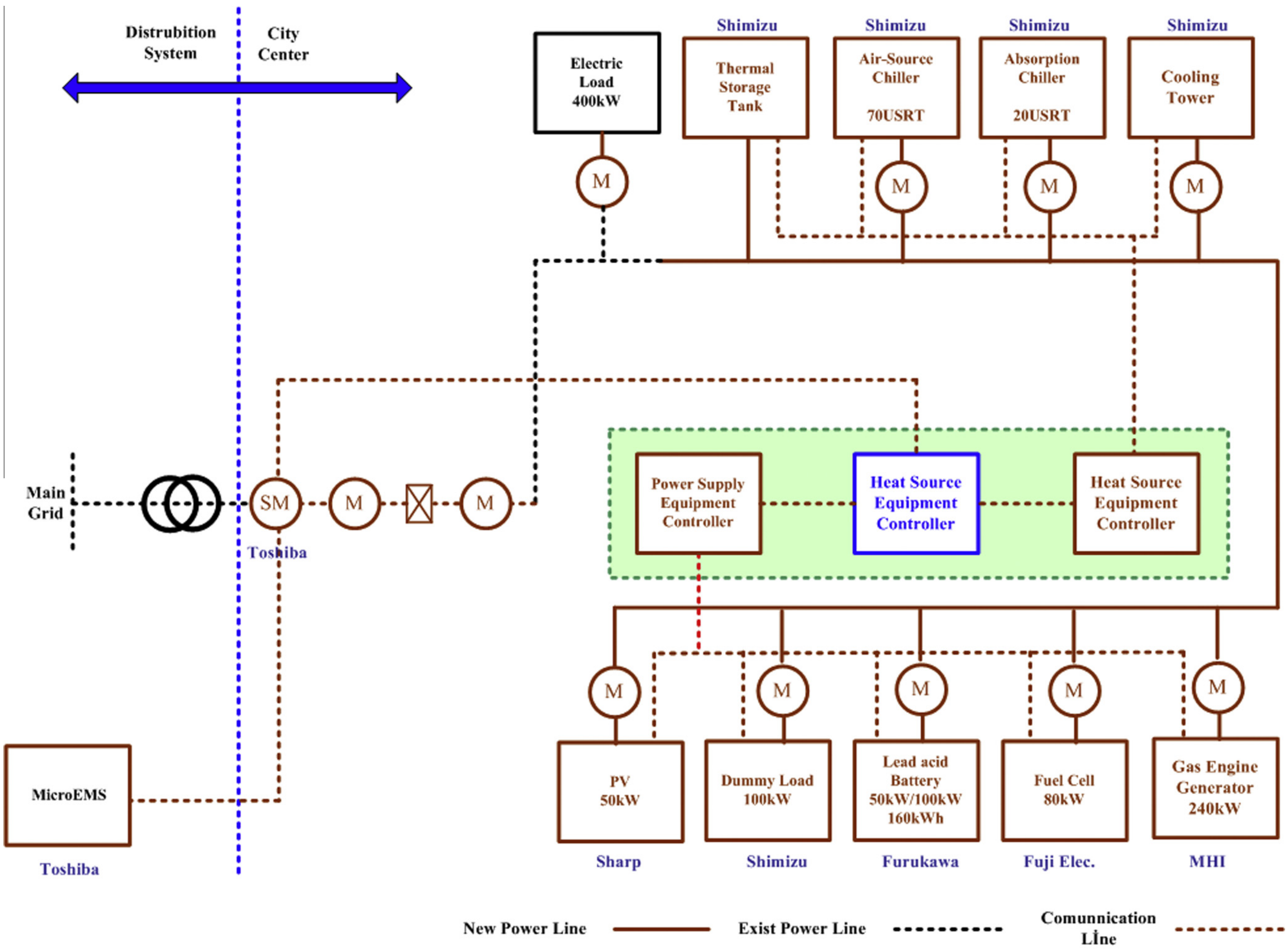

Fig. 4. Microgrid testbed at Albuquerque, New Mexico by Shimizu Corporation.

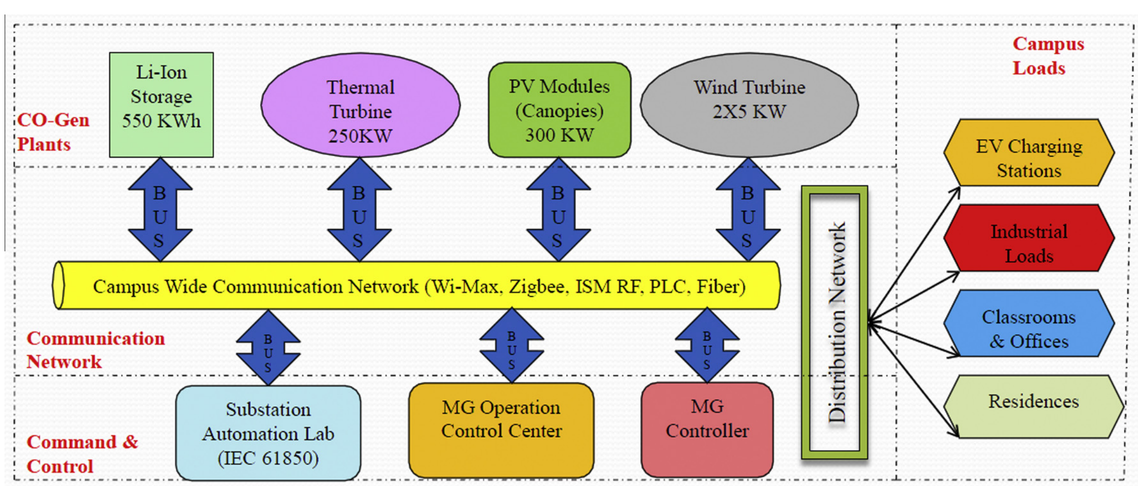

Fig. 5. Block diagram of British Columbia Institute of Technology microgrid.

electricity by using the stored hydrogen when the system requires. A battery bank (lead acid) is also integrated in the distribution line to maintain a fixed voltage on the line, therefore it simplifies the converter design. Furthermore, the aforementioned domestic microgrid is connected to other neighboring grids to exchange energy according to demand [34].

In the microgrid's Supervisory Control and Data Acquisition (SCADA) system, an M-340 programmable logic control (PLC) is installed as the main plant control platform. The controller is provided with data acquisition cards in order to communicate with the programmable load and power source, the plant devices and sensors. The communication between the DC/DC converters and

Table 6
Microgrid testbed at Japan.

Microgird Projects in Japan						
Project Name	Detail [Structure/Power Nature/Type]	DGs_Renewable	DGs_Nonrenewable	Control	Load	Storage
Aichi Microgrid, Tokoname	Radial/AC/Real	No	Gas	Centralized	Commercial/Industrial	a
Kyoto eco-energy Microgrid, Kythnos Island	Mesh/AC/Real	Gas	Diesel	Centralized	Residential	Battery
Hachinohe Microgrid, Hachinohe	Radial/AC/Real	Gas	No	Centralized	Commercial/Industrial	Battery
CRIEPI Microgrid, Akagi	Mesh/AC/Real	No	Diesel	Centralized	Static	No
Sendai Microgrid, Sendai	Radial/AC/Real	Gas	Diesel, Gas	Centralized	Residential, Commercial, Industrial	No
FC-CHP based Plant, Osoka	Campus/AC	No	Motor	a	a	a
Microgrid test facility in Yokohama, Japan	Remote/AC	Gas	No	a	a	Battery

a: No data found.

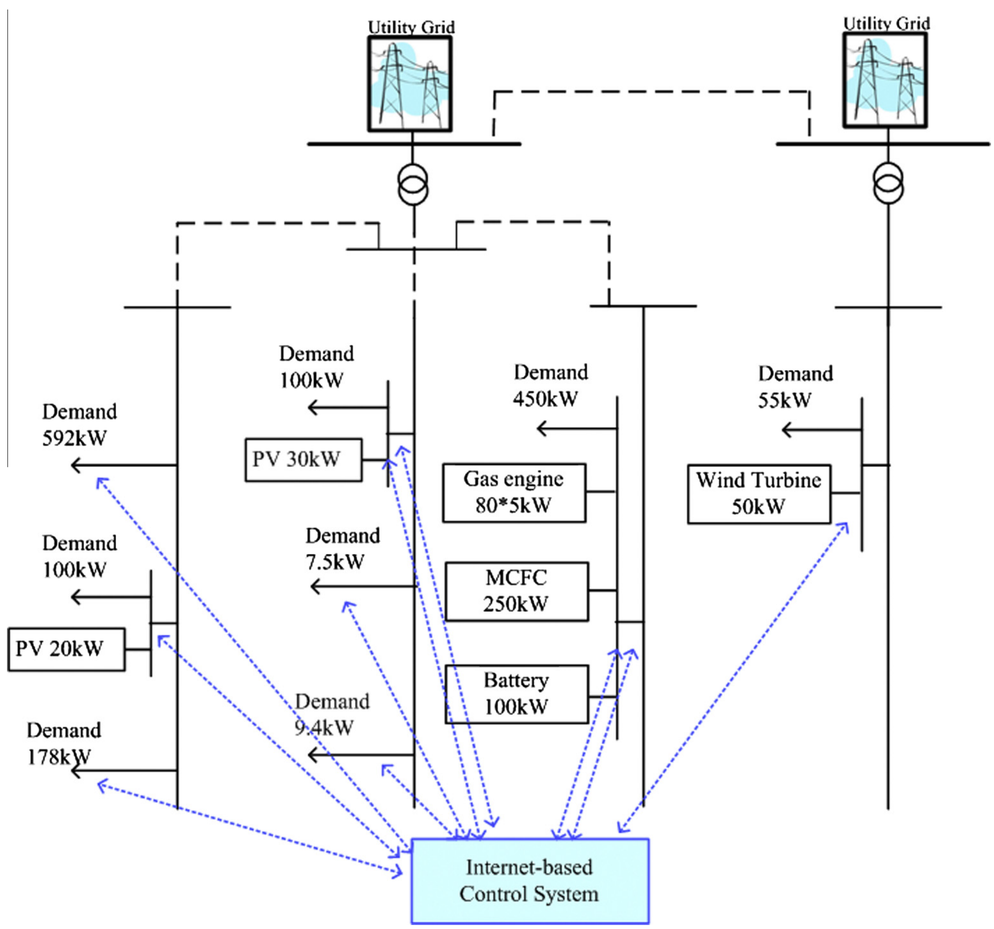

Fig. 6. The schematic diagram of Kyoto eco-energy microgrid.

the PCL is accomplished retaining the Canbus communication protocol.

3.4. Microgrid projects in rest of the world

Asian microgrids are mostly for remote application, where they focus on generating whatever amount of renewable energy is available for a reliable power system and later to maintain the stability and controllability of the system's nonrenewable DG or storage systems it has used. The central control method is one of the favorite control techniques in this region with few exceptions, such as in China where agent-based control techniques have also been used [16,38,39]. It is common practice to have centrally controlled microgrids or agent-based microgrids, which has been shown in detail in Table 8 [38,39].

The unique project of Korea has been installed by the Korean Energy Research Institute (KERI). The microgrid test facility is equipped with a photovoltaic simulator, fuel cells, diesel generators, and a wind turbine simulator along with various type of loads, storage and power quality devices. Besides, in Jeju Island a 230 MW microgrid was constructed in 2009 with a wind turbine and fuel cell. For the future implementation of microgrids in the

Table 7
Microgrid testbed at European Union.

Microgird projects in European Union						
Project name	Detail [Structure/Power Nature/Type]	DGs_Renewable	DGs_Nonrenewable	Control	Load	Storage
Bronsbergen Park Microgrid, Zutphen	Mesh/AC/Real	PV	No	Centralized	Residential	Battery
Am Steinweg Microgrid, Stutensee	Mesh/AC/Real	PV, CHP	No	Agent based	Residential	Battery
CESI RICERCA DER Testbed, Moneta	Radial/DC/Testbed	Solar Thermal, PV, Wind, /CHP	Diesel	Centralized	Residential	Flywheel, Battery
Kythnos Island Microgrid, Kythnos Island	Radial/AC/Real	PV	Diesel	Centralized	Residential	Battery
NTUA Microgrid, Athens	Radial/AC/Testbed	PV, Wind	No	Agent based	Static	Battery
DeMoTec Testbed, Kassel	Mesh/AC/Testbed	PV, Wind	Diesel	Agent based	Residential, Commercial, Industrial	Battery
University of Manchester Testbed, Manchester	Radial/AC/Testbed/Real	No	Motor	Centralized, Agent based	Static	Flywheel
Benchmark low voltage Microgrid, Athens	Radial/AC/Testbed	PV, Wind, Fuel Cell	No	Decentralized, Centralized	Residential	Flywheel, Battery
Nimbus Microgrid Testbed, Cork	Radial/AC/Testbed/Real	CHP, Wind, Fuel Cell	No	Centralized	Residential	Battery
Genoa University, Genoa	Mesh/AC/Testbed	PV, Wind, CHP	Gas	Decentralized	Residential	Battery
University of Nottingham Testbed, Nottingham	Radial/DC/Testbed	Wind	No	Decentralized	Residential	Battery
UT Comiegne (UTC) Tesrbed, Compiegne	Radial/DC/Testbed	PV, Fuel Cell	No	Decentralized	Motor	Battery
University of Seville Spain Testbed, Seville	Mesh/DC/Testbed	PV, Fuel Cell	No	Decentralized	Residential, Motor	Battery
FEUP Microgrid Testbed, Porto District	Radial/AC/Testbed	PV, Wind, Fuel Cell	Diesel	Centralized	Static	Battery

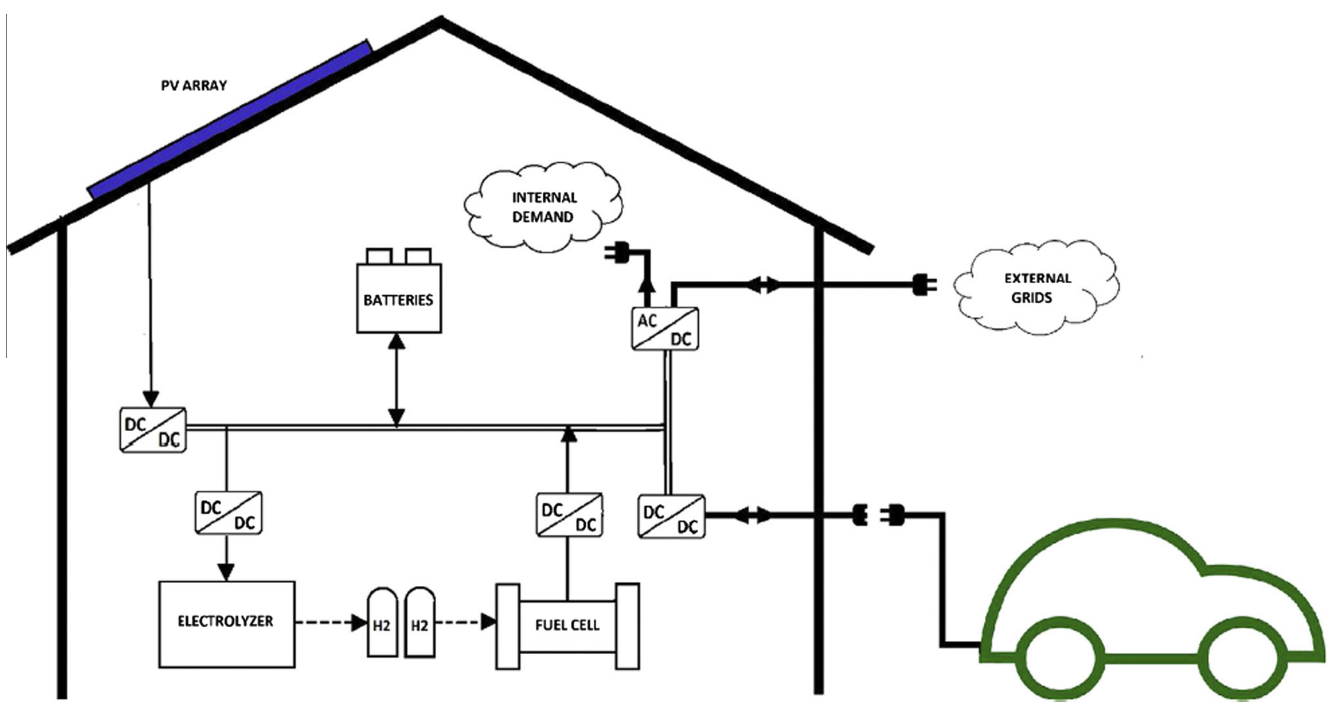

Fig. 7. Hydrogen based, domestic microgrid at University of Seville.

power network of Korea, the Jeju Island and analogous Korean islands are major applicants. Presently, very few remote distributed power systems are available, but there is a significant potential for microgrids in the near future. Besides, the government has already taken initiative and has invested a huge amount of financial support for researchers, and recently several microgrid projects have started. The Yungngora, Kalumburu and Windorah communities are examples of remote microgrids. Furthermore, some energy companies are currently planning and developing microgrids on several islands; for example Thursday Island in Queensland and King Island in Tasmania. The most remote microgrid project is currently going on in Western Australia where wind

Table 8
Microgrid Testbed in rest of the world.

Microgird Projects in rest of the world						
Project name	Detail [Structure/Power Nature/ Type]	DGs_Renewable	DGs_Nonrenewable	Control	Load	Storage
HFUT Microgrid, China	Mesh/AC/Testbed	PV, Wind, Fuel Cell, Hydro	Gas	Agent based	Static, Motor	Battery
Tianjin University Testbed, China	Radial/AC/Testbed	PV, Wind	Diesel	Centralized	Static	Battery
Test Microgrid at IET, India	Radial/AC/Testbed	Fuel Cell	No	Centralized	Static	No
MSEDCL at Wani Area Microgrid, India	Mesh/AC/Real	PV, Biomass	Diesel	Decentralized	Residential, Commercial,	No
INER Microgrid Testbed, Taiwan	Mesh/AC/Testbed/Real	PV, Wind	Diesel, Gas	Decentralized	Static, Motor	Battery
NUAA Testbed, China	Radial/AC/Testbed	PV, Wind	Motor	Centralized	Static, Motor	Battery
QUT Microgrid Testbed, Australia	Radial/DC/Testbed	PV, Wind	No	Decentralized	Residential, Motor	Battery

Table 9
Microgrid projects in Australia.

Microgrid detail		Primary energy resource	Capacity (kW)	Purpose
CSIRO, Newcastle	New South Wales	PV	110	Research
King Island	Tasmania	Solar	110	Remote Community
Kings Canyon	Northern Territory	PV	225	Tourism
Coral Bay	Western Australia	Wind	825	Remote Community
Bremer Bay	Western Australia	Wind	660	Remote Community
Denham	Western Australia	Wind	920	Remote Community
Esperence	Western Australia	Wind	3600	Remote Community
Hopetoun	Western Australia	Wind	1200	Remote Community
Rottnest Island	Western Australia	Wind	600	Remote Community

power is the most popular renewable source as shown in Table 9. Several microgrid testbed examples have been illustrated below.

3.4.1. NUAA microgrid testbed NUAA in China

The objective for the NUAA testbed is to analyze the smooth transition issue of microgrid systems based on the master–slave structure; the operation principle of the phase locked control strategy was studied in order to be realized in digital implementation. A devoted 100 kV A microgrid testbed was built to verify the microgrid control strategy and it was verified by experiment. In the master–slave configuration based microgrid, there is only one inverter performing as a master inverter, while the others are slaves controlled as current sources. The master inverter usually has two selectable operation modes: current controlled for grid-tied mode and voltage controlled for islanded mode. The test facility consists of a 2 kW single-phase photovoltaic inverter, a 17 kW three-phase photovoltaic inverter, and a 15 kW customer made wind simulation system consisting of a permanent-magnet motor-generator set, 100 kV A passive load bank and a 30 kV A active load unit, a programmable wind simulation to drive the motor to simulate different wind turbine performances, and a 15 kW three phase grid-tied wind turbine inverter for grid interface. Here the programmable DC power supplies and wind simulation converter are used in place of actual solar panels and wind turbine to maximize the flexibility of the testbed [3,37].

A high speed digital signal processor (150 MHz FPU) is used for the master inverter, whose input is coupled to a 700 V lead-acid battery array as shown in Fig. 8. A microgrid central control provides various functions such as information management and data acquisition, and system control of the microgrid. A high speed embedded PLC is used as the control platform for information management and data acquisition as a medium of communication.

3.4.2. Institute of Nuclear Energy Research, Taiwan (INER)

In Taiwan, the very first outdoor microgrid testbed was designed and implemented by the Institute of Nuclear Energy Research (INER) in 2009 with a capacity around 500 kW. This radial type microgrid consists of a wind turbine generator, high concentration PV, a gas turbine generator and battery.

Some of the key technologies of a distributed power system are wind turbine technology, PV module, stability and control techniques, power electronic converters, monitoring system and a protection scheme where huge research is going on around the world. Among them, the study on the operation mode of high concentration PV, voltage fluctuation and switching motor have already started, but with this project researchers have mainly focused on gas turbine operation mode and this study has carried on for both grid-tied and islanded modes [9].

The Institute of Nuclear Energy Research microgrid testbed was built for achieving several goals. These are:

(1) To demonstrate recent developments in renewable technologies by INER, for example high concentration PV and wind turbine generator.
(2) To analyze and test the DG inverters' properties in several anomalous circumstances.

This project has been selected for its critical structure to conduct various experiments on microgrids, such as isolated sensitive loads and non-sensitive loads, having both series and parallel feeders, used non-renewable distributed generation (gas turbine) to improve reliability, and used batteries for emergency backup plan of the system as well. The schematic diagram of INER hybrid microgrid testbed, which comprised of 18 AC buses and 4 DC buses, has been illustrated in Fig. 9.

In grid-tied mode, the gas turbines are deliberately operated in the active and reactive control mode and if islanding occurs, only turbines are moved to the V/f control mode while others' distributed generations follow their previous P/Q control mode. Robust control has been achieved by gas turbines to adjust amplitudes of voltage and frequency. Additional research has been done with the gas turbines' generators and batteries for both planned and

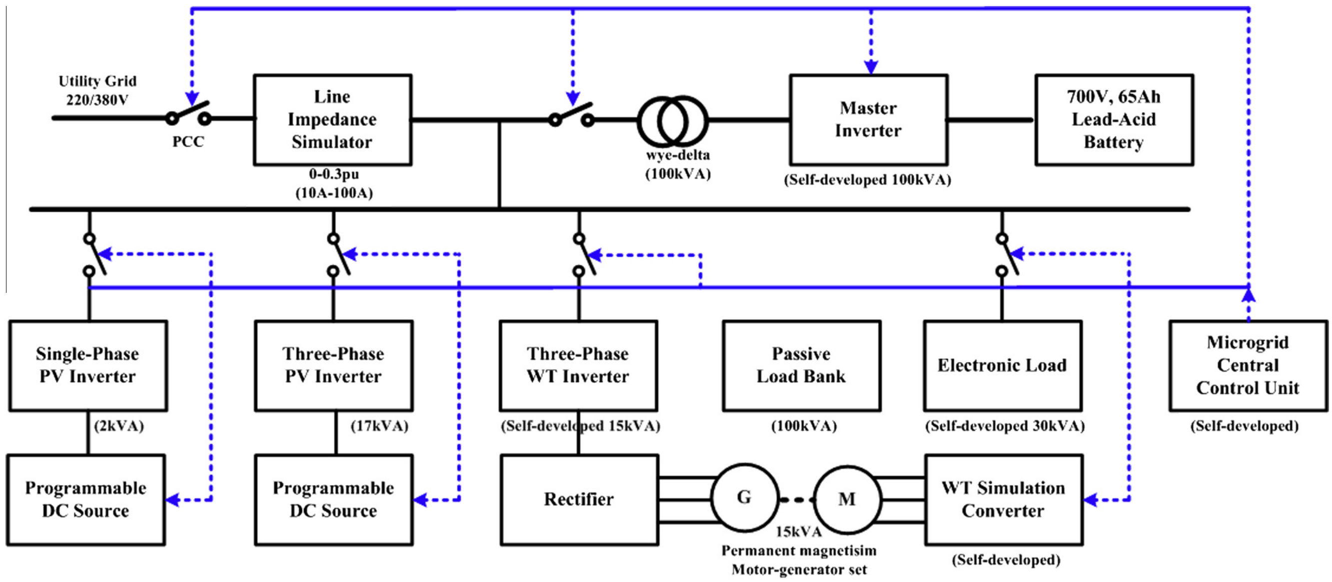

Fig. 8. Block diagram of microgrid testbed in China.

unplanned island conditions. In an islanded microgrid, the battery system has served as a master controller and the performance evaluation for both gas turbine generators inverters and battery systems has been conducted. For piloting experiments, the INER microgrid used both static loads and motor loads where a power line was used as a communication medium.

3.4.3. Test microgrid at the Institution of Engineering and Technology – India

One of the first Indian microgrid testbeds were installed around 2008 at the Institution of Engineering and Technology. The laboratory scale distributed system is comprised of fuel cells through particle swarm optimization based inverters, and 2.2 kW squirrel cage induction generators through a PWM inverter. The total capacity of the grid-tied test facility is 5 kW at 50 Hz. The schematic diagram of the microgrid test setup has been illustrated in Fig. 10. The sine of the PWM inverter has been used to sustain the V/f control and frequency of the designed microgrid. Information regarding any storage system or communication system has not been discussed in this project [6,37].

3.4.4. Microgrid testbed of Queensland University of Technology Australia

Queensland University of Technology Australia has already started developing one of the first institutional microgrid systems as shown in Fig. 11. This radial type hybrid microgrid is comprised of a nonrenewable distributed generation diesel generator and several renewable distributed generations, for example PV, FC and battery as a storage system. To control the test facility, researchers have used the decentralized power sharing droop control technique. There are four resistive heaters and six induction motors to use as a microgrid load. Besides, several kinds of loads such as the nonlinear load, unbalanced load and harmonic load have been used for experimental purposes at bus 5. Fuel cells will help to increase the power quality of DGs nearby where the nonlinear load is connected. Moreover, PV or battery can be used to compensate for power quality when nonlinear loads exist either at bus 3 of bus 4. The storage device and PV share power with the DG when the fuel cell is preferred as a compensator. Based on feeding power to a nonlinear load, the control system can adjust the mode of operation with any communication medium. Research shows that a low voltage DC distribution system, mainly dependent on PVs, can operate with the nonlinear loads and residential loads of a campus network. This nonlinear load study shows the feasibility of single phase residential electricity supply from a PVs and DGs based microgrid [11,14,45].

Table 10 presents a brief introduction of small microgrids around the World. The details of the microgrids are provided according to name, location, and foundation year. Furthermore, they are classified according to non-renewable and renewable based structures where the non-renewables are cited regarding generator types as diesel (D), stream (S), gas (G), hydro (H), and motor drive (M), while the renewable-based microgrids are expressed as wind, PV, fuel cell, and/or biogas sources. The microgrid types are presented as being located in remote (R), utility (U), or campus (C) areas. All parameters to be emphasized in the columns are indicated with an inverted comma, i.e., that means the first microgrid (Utsira Island Wind & Hydrogen Park) is supplied with wind and fuel cells in terms of renewable DGs, while the storage system is based on battery and flywheel. Table 11 shows the microgrid testbed projects expressing the completed year, total capacity, location, and source types. Furthermore, control, storage, and load types are also depicted in Table 11 where the communication types such as power line, Ethernet, optical, GSM or internet are expressed in a separate column.

Optimal Power Solutions (OPS) Inc. develops and implements renewable microgrids and utility storage projects. These include advanced optimizing operating cost and carbon footprint impacts on the global environmental system. It has installed high penetration renewable energy systems to meet the demands of specific locations and resolve environmental concerns as well. Numerous electrification projects at the rural and national level have been installed by OPS's proprietary. In recent times, OPS have developed advanced storage equipment suitable for connecting grid, solar, wind and storage [24]. A selection of significant projects completed since commencement is recorded in Table 12. The list of microgrid projects consists of inverter and renewable capacities besides the distributed generation method. The last columns present the application mode as off-grid or grid-tied, and installation years.

4. Findings of the study

After the study of numerous microgrid facilities, it is discovered that the majority of microgrid testbeds have used AC power for

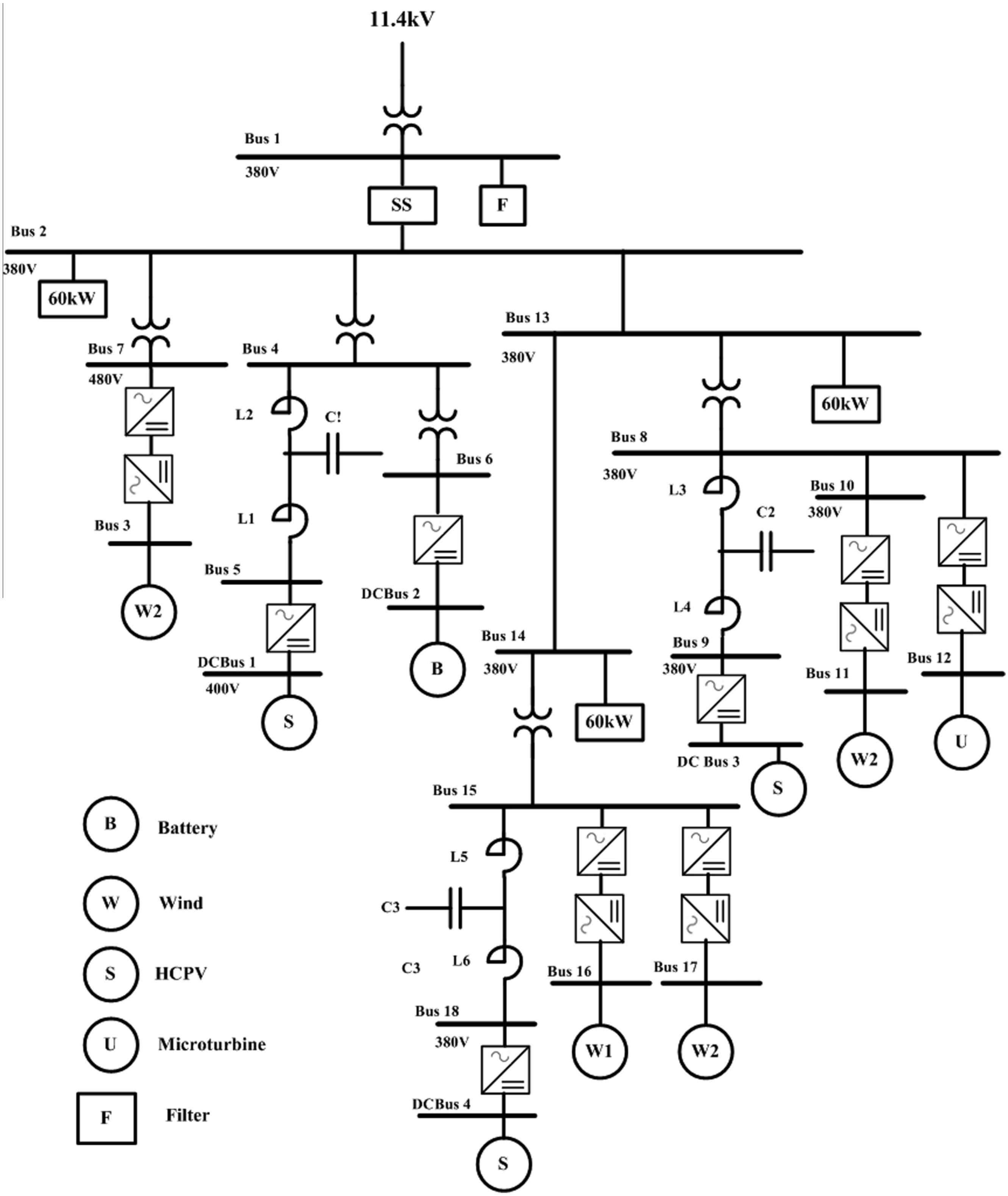

Fig. 9. One line diagram of institute of nuclear energy research microgrid.

electrification. So far the utility grid, the majority of electrical networks and loads are AC, which helps the AC distributed microgrid to participate with the utility grid without stress. However, one of the major concerns with AC systems is the power quality. Besides, the key advantage in a DC distribution system is fewer power quality problems and consequently fewer components and less complex control techniques are necessary. But, the application of a DC microgrid is not popular due to the inaccessibility of sufficient DC loads, the complexity of its protection system and huge transmission loss for any distantly distributed system [9,10].

The most frequently used DG sources in microgrid systems are solar PV, wind, micro-hydro, diesel and gas engine. Renew-

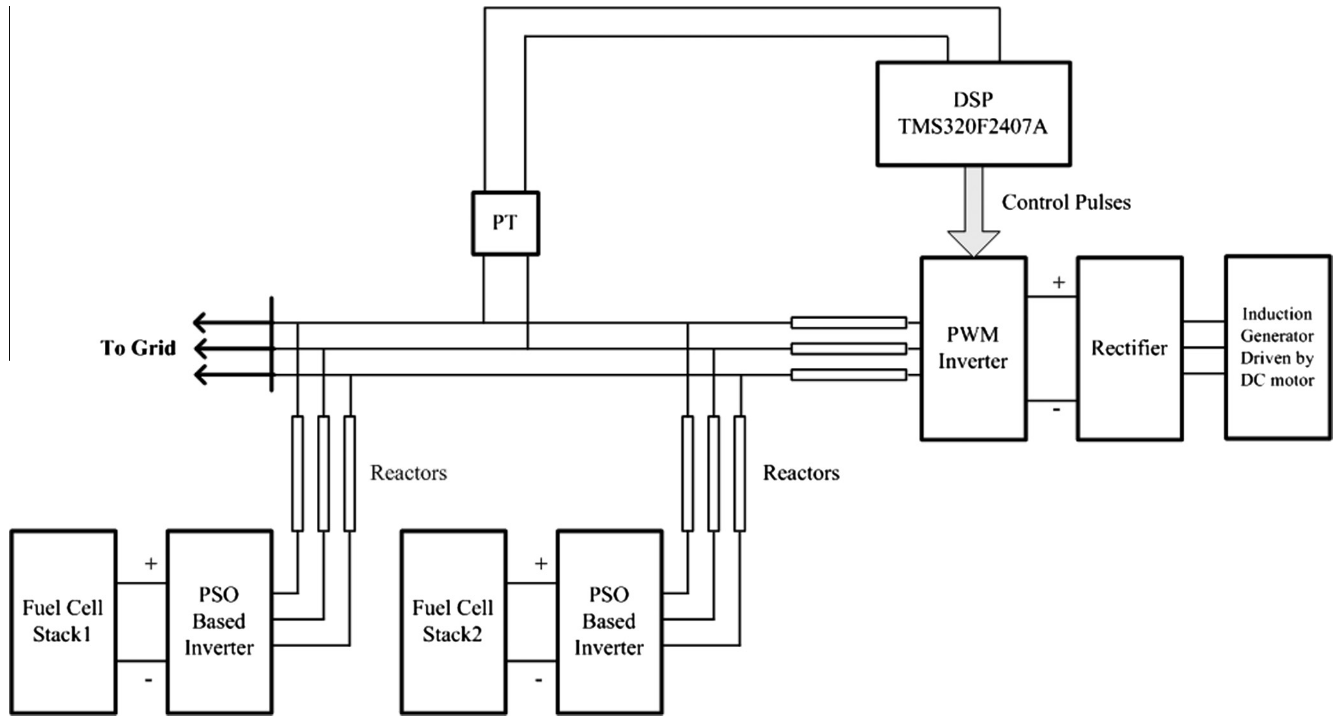

Fig. 10. Experimental microgrid at IET in India.

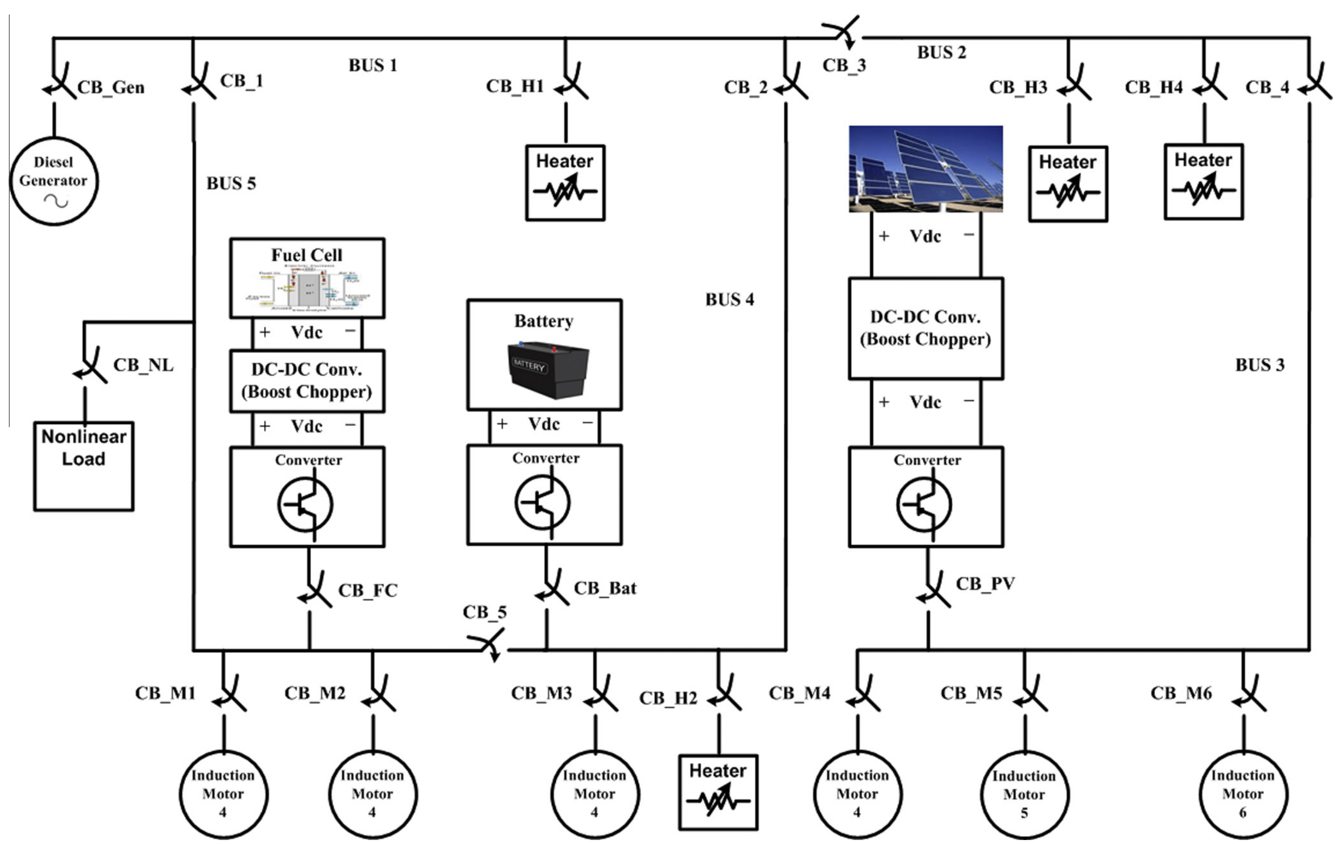

Fig. 11. The schematic diagram of the microgrid at Queensland University of Technology Australia.

able energy sources (RES) are reasonably popular as DG in European regions together with conventional sources. Power quality is an impending issue in a microgrid system. As the renewable DG sources are highly dependent on environment, the intermittent nature of resources leads to several PQ problems. Therefore, a consideration of PQ performance for any microgrid system is important where few microgrid testbeds have implemented power quality devices, as shown in the

Table 10
Several small microgrid around the World.

Several small microgrid around the world														
Detail				DGs_Nonrenewable	DGs_Renewable				Storage			Microgrid	Total	Remarks
Name	Place	Country	Year	Diesel[D], Stream[S], Gas[G], Hydro[H] Motor Driven Gen[M]	Wind	PV	Fuel Cell	Biogas	Battery	Flywheel	Capacitor	Type Remote[R] Utility[U] Campus[C] AC/DC	Capacity kW	
Utsira Island Wind & Hydrogen Plant	Utsira Island	Norway	2008	M	″		″		″	″		U, AC	2000	Grid-tie microgrid to supply for 10 houses
Hawii Hydrogen Power Park	Hawii	USA	2012		″	″	″		″			R, DC	200	Remote test facility.
FC-CHP based Plant	Osaka	Japan	2009				″					C, AC	300	For hot water supply
Mannheim-Wallstadt residential Plant	Mannheim	Germany	2003			″						R, AC	30	For shifting peak load
Continuon's MV/LV Plant	Holland	The Netherlands	2003			″			″			U, AC	315	To improve power quality
LABEIN's Commercial feeder Demonstration of Distributed Generation Technologies		Spain	2011	D, M	″	″				″	″	U, AC	200	
The Ílhavo Municipal Plant	Coimbra	Portugal	2009	D, M								u, AC	300	Analysis of microgrid behaviour
Kozuf Microgrid	Kozuf Mountain	Macedonia	2007			″		″				R, AC	5	For sleepfold and ski-centre
Dolan CM test bed	Ohio	USA	2002	M								U, AC	60	For emergency supply
San Diego Microgrid Plant	California	USA	2007	S, G		″						C, AC	18000	For campus supply
Santa Rita Jail Plant uninterrupted power	Dublin	USA	2011	D	″	″	″		″			U, AC	5000	For
Bornholm Multi microgrid	Lyngby	Denmark	2007	D, S	″	″	″	″				U, AC	55000	For stability & blackstart
EDP microgeneration facility		Portugal	2008	G	″	″						U, AC	50000	For illustrating microgrid
Eigg island plant		Scotland		H	″	″				″		R, AC	144	For island power supply
Microgrid test facility in Yokohama		Japan	2008	G	″	″		″	″			R, AC	100	For Yokohama research Institute
CSIRO Energy center	Newcastle	Australia	2010	G	″	″			″			U, AC	500	For supporting supply
Singapore pulau ubin microgrid	Pulau Ubin	Singapore	2011	D		″			″			U, AC	1000	For domestic apply
Korea KEPRI microgrid project	Yuseong-gu	Korea	2011	D, G		″			″			U, AC	400	For planning of future construction and operational
KERI Microgrid System establishment of pilot microgrid	Jeju Island	Korea	2008	D	″	″	″		″			R, AC	100	For
San Juanico Plant	San Juanico	Mexico	2004	D	″	″						R, DC	200	For remote community
Manzanita Hybrid Power Plant	California	USA	2005		″	″			″			U, AC	15	For community power supply
Sunwize Power Plant	a	Canada		D	″	″			″			R, AC	15	Standby Power system
Santa Cruz Island	California	USA	2005	D		″			″			R, DC	300	For US Navy

(*continued on next page*)

Table 10 (*continued*)

Several small microgrid around the world														
Detail				DGs_Nonrenewable	DGs_Renewable				Storage			Microgrid	Total	Remarks
Name	Place	Country	Year	Diesel[D], Stream[S], Gas[G], Hydro[H] Motor Driven Gen[M]	Wind	PV	Fuel Cell	Biogas	Battery	Flywheel	Capacitor	Type Remote[R] Utility[U] Campus[C] AC/DC	Capacity kW	
Xcalac Microgrid	Xcalac	Mexico	1992		″				″			R, DC	150	For village supply
Campinas Microgrid	Campinas	Brazil	2001	D		″			″			R, DC	150	For residential supply
Azores Island Plant	Azores	Portugal	2005	D, H	″	″						U, AC	2000	For increasing grid stability
SGEM “Hailuoto” Microgrid	Hailuot	Finland	2012	D	″							U, AC	2000	For locally support of grid
Woodstock Microgird	Minnesota	USA	2001		″	″			″			U, AC	5	For maintaining shop & office
Gazi University Energy park	Ankara	Turkey	2007		″	″			″			C, AC	5	For feeding laboratory
Mt. Newall Microgid	Mt. Newall	Antarctica	2002	D	″	″						R, AC	10	For science foundation station project
Isla Tac Microgid plant	Isla Tac	Chile	2002	G	″				″			R, AC	40	For islanded community
Subax residential microgrid	Subax	China	2006	G, D	″	″			″			R, AC	50	For isolated community
Dangling Rope Marina Microgrid	Utah	USA	2001			″							160	For national park center
Kotzebue Microgrid Plant	Alaska	USA	1997	D	″							R, AC	11000	For remote area application
Alto Baguales Microgrid Plant	Coyhaique	Chile	2001	D, H	″							R, AC	23000	For remote power supply
Wales Alaska Power Plant	Alaska	USA	2002	D	″				″			R, AC	500	For rural community supply
St. Paul Power Plant	Alaska	USA	1999	D	″							R, AC	500	For industrial/ airport facility
Ascension Island Power Plant	Ascension Island	Canada	1996	D	″							R, AC	225	For Island community

summary of the review. Hence, supplementary research is essential to improve microgrids’ PQ issues as well as stability and reliability issues to increase the performance and power quality of microgrid systems.

The storage system is one of the most important choices for the successful and stable operation of a microgrid. Although the battery banks are the most popular ones, some of the existing testbeds have various sorts of storage devices such as a flywheel or super capacitors. Few of them have a combination of several storage units together and very few systems are without any storage unit where a controllable DG source is present. Grid-tied connection is important when a renewable distributed system short of storage device needs to maintain system stability.

Key benefits of the microgrid:

- The foremost benefit of the microgrid is its ability to operate in islanded mode when there is any disturbance in the utility grid, or for economical purposes. Hence, it increases the overall system reliability [38].
- During peak load time, the microgrid helps the utility grid to function properly by sharing its loads, hence failure of the utility grid can be prevented.
- Microgrid utilities use local green energy to feed local demand instead of using fossil fuel, hence lowering its carbon footprint.
- Opportunity for big customers/companies to improve power quality and power stability.
- Small (microgrid) macrogrids are easy to control. The microgrid usually used on the West coast grids acts as a capacity driver, and East coast grids as a power quality and stability issue. However, in Chicago the microgrid has both uses.
- Combined heat and power (CHP) with a non-renewable generator helps to improve overall efficiency [36].
- In the microgrid system, users can produce their demanded energy, which mitigates the electricity costs.
- A microgrid can remove stress from a macrogrid.
- Generation and demand are happening at the distribution level without transmission. Hence, it reduces the network and transmission losses and provides local voltage support as well.

Several problems of the microgrid:

- It is hard to maintain the standard level of voltage, frequency and power quality while continuing to maintain balance with intermittent supply and variable demand.

Table 11
Summary of microgrid projects.

Summary of microgrid project																								
Situation	DGs renewable										DGs Microturbine	Microgrid application	Distribution type	Power nature	Microgrid type	Control			Load			Storage	Communication	Remarks
Name	Place	Country	Year	Total capacity/ Renewable MW	Solar thermal	PV	Wind	Fuel cell	CHP	Hydro[″]/ Others[Name]	Diesel[D] Stream[S] Gas[G] Motor Driven Gen[M]	Facility(Campus/ Industrial)[C]/ Remote[R]/ Utility[U]	Mesh[M]/ Radial[R]	AC/DC	Real[R]/ TestBed[TB] Both[B]	Centralized	Decentralized (Autonomous)	Agent based	Residential[R]/ Commercial[C]/ Industrial[I]	Static	Motor/ Electronics	Battery [B] Flywheel[FW] Capacitor[C] Others[Name]	Power Line[PL] Others[Name] Optical Fiber Network[OP] NO	
Boston Bar – BC Hydro	British Columbia	Canada	2008	15						″	D	U	R	AC	R		″		R				Telephone	To improved reliability and supply security
Boralex Plant	Qubee	Canada	2005	31							S	U	R	AC	R		″		R				a	For replacement feeder
CERTS Testbed	Ohio	USA	2009	0.2							G	C	M	AC	TB		″		R			B	Ethernet	To demonstration of Microgrid
UW Madison Testbed	Wisconsin	USA	2008	0.02		″					D	C	R	AC	TB		″			″		B	Ethernet	To develop robust plug-and-play power control
Bronsbergen Park Microgrid	Zutphen	The Netherlands	2009	0.3		″						R	M	AC	R	″			R			B	GSM	To provide power holiday park
Am Steinweg Microgrid	Stutensee	German	2005	0.2		″			″			U	M	AC	R			″	R			B	Internet Protocol	For residential power supply
CESI RICERCA DER Testbed	Moneta	Italy	2006	0.5	″	″	″		″		D	U	R	DC	TB	″			R			B, FW	PL, Wireless	To perform different experimentations
Kythnos Island Microgrid	Kythnos Island	Greece	2001	0.05		″					D	R	R	AC	R	″			R			B	PL	To supply remote island
NTUA Microgrid	Athens	Greece	2004	0.01		″	″					C	R	AC	TB			″		″		B	PL	For microgrid research
DeMoTec Testbed	Kassel	German	2002	0.2		″	″				D	C	M	AC	TB			″	R, C			B	Ethernet	For investigating renewable technology
University of Manchester Testbed	Manchester	UK	2005	0.2							M	C	R	AC	B	″		″		″		FW	PL	For microsource interface with storage
Aichi Microgrid	Tokoname	Japan	2005	1.2		″		″		Biogas		C	R	AC	R	″			C, I			B	PL	To maintain airport supply
Kyoto eco-energy Microgrid	Kythnos Island	Japan	2005	0.4		″	″	″			G	U	M	AC	R	″			R			B	Ethernet	Power generator from biogas
Hachinohe Microgrid	Hachinohe	Japan	2005	1		″	″			Biomass	G	U	R	AC	R	″			C, I			B	PL	For increasing power quality
CRIEPI Microgrid	Akagi	Japan	2003	0.3		″						U	M	AC	R	″				″		No	OP	SVC & SVR regulate voltage
Sendai Microgrid	Sendai	Japan	2006	1		″		″			G	U	R	AC	R	″			R, C, I			No	GPS	To demonstrate power quality by PQR
HFUT Microgrid	Anhui	China	2006	0.3		″	″	″		″	D	C	M	AC	TB			″		″	″	B	Profibus	Emulation platform for Microgrid
Tianjin University Testbed	Tianjin	China	2007	0.005		″	″					C	R	AC	TB	″				″		B	RS 485	For experimentation purpose
Test Microgrid at IET	a	India	2008	0.005				″			M	C	R	AC	TB	″				″			a	Storage & Communication aren't discussed
Benchmark low voltage Microgrid	Athens	Greece	2002	0.1		″	″	″				U	R	AC	TB	″	″		R			B, FW	NO	For simulation of multi-feeder microgrids
VSC feeded Microgrid	Toronto	Canada	2006	0.01							M	C	R	AC	TB		″			″	″	C	NO	Study on VPD/ FQB control scheme
University of Miami Testbed	Florida	USA	2007	0.01		″		″				C	R	DC	TB		″		R			B	NO	Hierarchical hybrid Microgrid paradigm
Nimbus Microgrid Testbed	Cork	Ireland	2006	0.2			″	″	″			U	R	AC	B	″			R			B	Wireless	Strategic resource for CIT & Research purpose
MSEDCL at Wani Area Microgrid	Maharashtra	India	2011	18.5		″				Biomass		U	M	AC	R		″		R, C, I				PL	For supporting utility grid
INER Microgrid Testbed	Longtan	Taiwan	2009	0.5		″	″				G	C	R	AC	B		″			″	″	B	PL	Battery and gas turbine provide stability

(*continued on next page*)

Table 11 (*continued*)

Summary of microgrid project

Situation	DGs renewable										DGs Microturbine	Microgrid application	Distribution type	Power nature	Microgrid type	Control			Load			Storage	Communication	Remarks
Name	Place	Country	Year	Total capacity/ Renewable MW	Solar thermal	PV	Wind	Fuel cell	CHP	Hydro[″]/ Others[Name]	Diesel[D] Stream[S] Gas[G] Motor Driven Gen[M]	Facility(Campus/ Industrial)[C]/ Remote[R]/ Utility[U]	Mesh[M]/ Radial[R]	AC/DC	Real[R]/ TestBed[TB] Both[B]	Centralized	Decentralized (Autonomous)	Agent based	Residential[R]/ Commercial[C]/ Industrial[I]	Static	Motor/ Electronics	Battery [B] Flywheel[FW] Capacitor[C] Others[Name]	Power Line[PL] Others[Name] Optical Fiber Network[OP] NO	
Genoa University	Genoa	Italy	2013	0.2		″	″		″		G	C	M	AC	TB		″		R			B	OP	Testbed for campus, industries &manufactures
Sandia National Lab Testbed	Washington, DC	USA	2012	0.06		″	″				D	C	R	DC	TB		″		R	″		Emulator	Ethernet	High penetration stochastic renewables
NUAA Testbed	Nanjing	China	2012	0.1		″	″				M	C	R	AC	TB	″				″	″	B	PL	Evaluate the control methods
University of Nottingham Testbed	Nottingham	UK	2011	0.5			″					C	R	DC	TB		″		R			B	LAN, GPRS	A real time microgrid emulator
UT Arlington Testbed	Texas	USA	2011	0.01		″	″	″			D, G	C	R	DC	TB		″		R	″		B	PL	For advanced research platform for US Navy
FIU Testbed	Florida	USA	2008	0.01		″	″	″			M	C	R	DC	TB	″		″	R		″	FW	PL	Hybrid grid to optimize operating techniques
Laboratory scale microgrid testbed	New Jersey	USA	2011	0.01		″						U	R	AC	R	″			R		″	B	Wireless	Generator Emulation Controls for stabilizing grid
UT Austin	Texas	USA	2010	5							D, G, M	C	R	AC	TB		″			″	″	FW	NO	Shipboard power systems
UT Compiègne(UTC) Testbed	Compiègne	France	2011	0.01		″		″				C	R	DC	TB		″				″	B	PL	Building-integrated microgrid for stable power
University of Seville Spain Testbed	Seville	Spain	2012	0.01		″		″				C	M	DC	TB		″		R		″	B	CAN bus	Representation of longterm performance
QUT Microgrid Testbed	Queensland	Australia	2010	0.015		″		″			D	C	R	DC	TB		″		R		″	B	NO	To investigate microgrid power quality
Microgrid testbed at Albuquerque	New Mexico	USA	2010	2.5		″		″	″		G	U	R	AC	R		″		R, C		″	B	PL	To support commercial area load
Utility Microgrid at Los Alamos	New Mexico	USA	2011	2.5		″						U	R	AC	R		″		R			B	OP	US-Japan Collaboration project for Microgrid
RIT Microgrid	New York	USA	2013	0.6		″	″	″		Biogas		C	M	AC	TB		″		R	″	″		PL	Geothermal is used to warm up/ cool down buildings
Mad River Park Microgrid	Vermont	USA	2005	0.5		″					D, M	R	M	AC	R		″		R, C, I			B	a	Reliable power around Mad River microgrid
Palmdale water district power system	California	USA	2006	4			″			″	D, G	U	R	AC	R		″		R, C	″	″	C	a	Energy bridge of renewables & DG technologies
Ramea wind-diesel Microgrid	NL	Canada	2004	3.5			″				D	R	M	AC	R		″		R			B	Wireless	Power for remote fishery community
Fortis-Alberta Microgrid	Alberta	Canada	2006	7			″			″		U	R	AC	B	″			I			a	a	Industrial-grade microgrid prototype
BCIT Microgrid	BC	Canada	2008	1.2		″	″				S	C	R	AC	B	″			R, I	″	″	B	PL, Fiber	Addressing critical issues of microgrid
Hawaii Hydrogen Power park	Hawaii	USA	2013	0.03		″	″	″				R	R	DC	TB	″			R	″		B	NO	Small-scale DG systems fueled by hydrogen.
FEUP Microgrid Testbed	Porto District	Portugal	2005	0.1		″	″	″			M	C	R	AC	TB	″			R			B	PL	Campus microgrid for research purpose

a: No data found.

Table 12
List of selected microgrid projects by Optimal Power Solutions Inc.

Microgrid project of Optimal Power Solutions Inc (OPS)						
Location	Project manager	Inverter capacity	Renewable capacity	Distributed generation	Application mode	Time
Maluku & Makassar Islands-Indonesia	PLN Utility, Indonesia	500 kW	700 kW	Solar PV, Diesel, Hybrid	Off-grid	2012
Maluku Islands-Indonesia	PLN Utility, Indonesia	250 kW	225 kW	Solar PV, Diesel, Hybrid	Off-grid	2012
South India	BHEL	10 MW	10 MW	Solar PV	Grid-tied	2012
India	BHEL, India Bulls	6 MW	6 MW	Solar PV	Grid-tied	2012
Lakshadweep, Bangaram Islands-India	BHEL	1.1 MWp	2 MWp	Solar PV, Diesel, Hybrid	Off-grid	2012
Marampit Province-Indonesia	PLN Utility, Indonesia	75 kW	150 kWp	Solar PV, Diesel, Hybrid	Off-grid	2012
Maluku Province-Indonesia	PLN Utility, Indonesia	275 kW	405 kW	Solar PV, Diesel, Hybrid	Off-grid	2012
Morotai Island, Moluccas-Indonesia	PLN Utility, Indonesia	1.35 MW	600 kW	Solar PV, Battery	Off-grid	2011
Raichur, Karnataka-India	BHEL, India	3 MW	3 MW	Solar PV Grid Connect	Grid-tied	2011
Bunaken, Indonesia	PLN Utility, Indonesia	215 kW	353 kW	Solar PV, Diesel, Hybrid Off Grid	Off-grid	2011
Karnataka-India	KPCL-State Utility	3 MW	3 MW	Solar PV Grid Connect	Grid-tied	2010
Kinabatagan, Sabah-Malaysia	KKLW Rural Ministry	980 kW	220 kW	PV, Diesel	Off-grid	2010
Superior Valley-USA	Private Client	180 kW	120 kW	Solar PV	Grid-tied	2010
Over Yonder Cay Island-Bahamas	Private Client	600 kW	360 kW	PV, Wind, Diesel	Off-grid	2010
Raj Bhavan Governor House-Kolkata	WBGEDCL, Ministry of New & Renewable Energy	5 kW	1 kW	Solar PV	Grid-tied	2009
Jamuria-West Bengal	Disargarh Power Corporation (DPC)	2 MW	2 MW	Solar PV	Grid-tied	2009
Telupid, Sabah (Malaysia)	Ministry of Education Malaysia	105 kW	100 kW	Hybrid Power Conditioner	Off-grid	2009
Kalabakan, East Sabah (Malaysia)	TNB-ES, Ministry of Education	555 kW	250 kW	PV, Diesel	Grid-tied	2009
Idaho-USA	Idaho Power-US Air Force	150 kW	77 kW	PV, Diesel	Off-grid	2008
Orang Asli Project-2, Malaysia	TNB-ES Malaysia	90 kW	45 kW	PV, Diesel	Off-grid	2008
Hyrid Power Systems-Indonesia	PT Len	150 kW	–	PV, Diesel	Off-grid	2007
Indonesia	PT Nabgunbaskara	20 kW	–	Hybrid Power Conditioner	Off-grid	2007
Orang Asli Project-1, Malaysia	TNB-ES Malaysia	285 kW	138 kW	PV, Diesel	Off-grid	2007
Villages Sabah Power Systems, Malaysia	TNB-ES Malaysia	225 kW	105 kW	PV, Diesel	Off-grid	2007
PulauTinggi, Mersing-Malaysia	TNB-ES Malaysia	90 kW	40 kW	PV, Diesel	Off-grid	2007
Perhentian Island-Malaysia	TNB-ES Malaysia	450 kW	280 kW	PV, Wind and Diesel	Off-grid	2007
School Sabah Power Systems-Malaysia	Ministry of Education	225 kW	190 kW	PV, Diesel	Off-grid	2007
Arizona-USA	APS – Greywolf Project	90 kW	40 kW	PV, Diesel	Off-grid	2006
Bandung-Indonesia	Alstom	145 kW	–	GSC Systems	Off-grid	2006
Lighthouse Locations-Indonesia	Ministry Project	260 kW	–	PV, Diesel	Off-grid	2006
Philippines	Dumalag/Matec	40 kW	30 kW	Hybrid Power Conditioners	Off-grid	2006
Santa Cruz Island, USA	United States Navy	90 kW	137 kW	PV, Diesel	Off-grid	2005
Lakshadweep Islands, India	BHEL, India	60 kW	25 kW	PV, Diesel	Off-grid	2005
Mersing Islands, Malaysia	TNB-ES Malaysia	360 kW	85 kW	PV, Diesel	Off-grid	2004

- For reliability purposes, a storage device is required which occupies more space and maintenance.
- It is difficult to achieve synchronization with the utility grid.
- A distributed system could create stress for the macrogrid when it operates as a load.
- A sophisticated protection system is the challenge in implementing the microgrid.
- The microgrid has critical issues for example, standby charges and net metering – which need to be addressed [18,22].
- A better interconnect standard is needs to be developed for keeping consistent with IEEE P1547.
- Adding more uncertain sources (like wind, solar) means it is much more difficult to control centrally (Eastern/Western grid), but it is easy to control locally by knowing the behavior of the load.
- Utilities produce more fossil power after monitoring that more solar/wind power is connected to the system because of its intermittent nature.
- Huge harmonics effects from the inrush current of transformers or Induction machine [37].
- Three phase unbalance could occur from single phase loads of single phase generators such as photovoltaic [18].
- Several features are required to achieve flexibility of the microgrid [17]:
- The microgrid should be capable of following the voltage ride-through standard of that particular area.
- It is very important to have a black-start quality if the system needs to restart for natural disaster or maintenance purposes.
- The microgrid needs to estimate grid impedance prior to something being connected or disconnected to it.
- The most important feature which would give the microgrid better control is storage energy management and a comprehensive control system.

5. Conclusion

Right now, modern nations produce the majority of their power in expansive unified offices, for example, fossil fuel, atomic or hydropower plants. These plants have great economies of scale, however generally transmit power across long separations and contrarily influence nature. Most plants are manufactured thusly because of various monetary, health & security, logistical, natural, land and topographical variables. The dispersed era is an alternate methodology. It diminishes the measure of power lost in transmitting power in light of the fact that the power is created quite close to where it is utilized, maybe even in the same building. This additionally decreases the size and number of force lines that must be developed. Previously, these attributes required devoted hard-working architects and expansive complex plants to lessen contamination. On the other hand, the recently installed frameworks can provide these qualities by computerized operation and renewable sources such as solar, wind and geothermal. These improvements decrease the requirements that are needed to increase the efficiency [7,31].

Different tests are required to achieve a cleaner and more secure transmission framework, while the administration framework should be handled by comparative exploration ventures. The results of studies performed on microgrids will support the improvement of secure, solid, and stable genuine systems with more terrific entrance of RE sources. This will be supportive in accomplishing a more solid, secure and cleaner power without bargaining on environmental assurance and comparable ideas.

Research into microgrids has been developed everywhere throughout the world. Thusly, a few nations, for example, Canada, Japan and USA are occupied with a few exploration tasks managing microgrids. Around the exploratory microgrids being mulled over, it has been demonstrated that the greater part of the microgrids actualized utilization of AC transmission frameworks with centralized controls. It has likewise been seen that islanded microgrids assume an essential part in rustic jolt ventures everywhere throughout the world. At long last, various issues, for example, circuit insurances, DC dispersion frameworks and optimal operation of the entire framework still require an extraordinary arrangement of committed research to certify a suitable improvement of microgrids later on [40,41].

The DC microgrid is not extremely prominent in European districts, however it has points of interest with respect to lesser force quality issues; more stress ought to be provided for this framework. The fundamental boundary to extend this innovation is of lesser measure than DC burdens. A large portion of the existing AC microgrid testbeds have incorporated electric storage devices as space units, however it is impractical; further mechanical change can help the framework to end up financially practical. More use of RESs is normal in microgrid frameworks as they are very nearly contamination-free and hence environmentally friendly. All things considered, potential exertion ought to be provided to take care of force quality issues associated with the renewable power sources. The fusion of distinctive renewable frameworks plus space has a potential future in light of the fact that it serves to store the clean power at whatever point is accessible. The progression in reserve and electric storage device frameworks looks encouraging as far as expense and engineering go. Despite the fact that introductory framework expenses and operation and upkeep expenses may be higher, recognizing the necessities of interest on the side of administration and augmenting the utilization of accessible RESs, microgrids with space units could be a feasible choice within a brief period of time.

This paper has displayed the ebb and flow status of the literary works related to microgrid examination. It has depicted the microgrid thought and the inspirations driving its usage then delineated the diverse examination fields under this heading. The current exploration work was condensed to give a general understanding about the present level of the information. At long last, conceivable examination zones have been proposed which are fundamental for future improvement.

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