A Comprehensive Study on Microgrid Technology

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Abstract- Grid connection capability of distributed generation attracts researchers due to the cumulative demand for electricity and environment pollution concern as a new emerging technology for providing reliable and clean power supply. A microgrid comprises distributed generation, energy storage, loads, and a control system that is capable of operating in grid-tied mode and/or islanded mode. As operation modes are shifted, the microgrid should successfully manage the voltage and frequency adjustment in order to protect the grid and any loads connected to the system. Facilitation of the generation-side and load-side management and the resynchronization process is required. This paper presents an overall description and typical distributed generation technology of a microgrid. It also adds a comprehensive study on energy storage devices, microgrid loads, interfaced distributed energy resources (DER), power electronic interface modules and the interconnection of multiple microgrids. Details of stability, control and communication strategies are also provided in this study. This article describes the existing control techniques of microgrids that are installed all over the world and has tabulated the comparison of various control methods with pros and cons. Moreover, it aids the researcher in envisioning an actual situation using a microgrid today, and provides insight into the possible evolvement of future grids. In conclusion, the study emphasizes the remarkable findings and potential research areas that could enrich future microgrid facilities.
Keywords- Microgrid; Distributed energy resources; Distributed generation technology; Future grid.

1. Introduction

A microgrid is a modern distributed power system using local sustainable power resources designed through various smart-grid initiatives. It also provides energy security for a local community as it can be operated without the presence of wider utility grid. Microgrid technology generally represents three important goals of a society such as reliability (physical, cyber), sustainability (environmental considerations), and economics (cost optimizing, efficiency). The “distributed generation” (DG) term refers to power generation located at or near the consumption sites. By comparison to “central generation”, DG can eliminate the generation, transmission, and distribution costs while increasing efficiency by removing elements of complexity and interdependency. In many cases, distributed generators can provide lower generation costs, higher reliability, and increased security not realized via traditional generators. For instance, Pike Research has identified 3.2 gigawatts (GW) of globally existing microgrid capacity [1-4]. The North America leads to global microgrid generation with 2,088 MW operating capacity according to the report [3]. On the other hand, Europe holds the second rank with 384 MW installed microgrid capacity while Asia Pacific follows with 303 MW of operating capacity. The installed microgrid capacity in the rest of world is around 404 MW. If each power user (building/company/hospital/market) cares about reliable power and keep their desire to back up energy source like generation/battery/diesel engine that would be the most expense power system. In a microgrid system, backup resources are unnecessary because a single user does not have to supply a general load during critical consumption periods. One billion dollars of energy consumption can be conserved by managing a few hundred-summer peak hours by shifting or eliminating loads. Therefore, reliability is a major justification for microgrid operation [1]. Microgrids could also prove economically viable in the southwestern US. The sustainability is another most important factor for considering this new technology, but less so, in the US; it is more necessary in China where a great deal of environment issues is emerging nowadays. The microgrid could tackle the energy crisis since the transmission losses are greatly reduced. Additionally, a microgrid provides significant reduction in generation costs while providing reliable and sustainable energy to loads. The cyber security issue is addressed as well due to the localized nature of the system. Microgrid technology is suitable for regions with an underdeveloped transmission infrastructure, such as remote villages where an islanded microgrid would be the most advantageous kind of power network [4].

Microgrids that are similar to a conventional grid structure in terms of power generation, distribution, transmission, and control features are assumed as a minor model of actual grid form. However, microgrid technology differs from a conventional grid owing to the distance between power generation and consumption cycles as a microgrid is installed near the load-sites. Microgrids also integrate with distributed generation plants such as combined heat and power (CHP), and renewable energy plants powered by solar energy, wind power, geothermal, biomass, and hydraulic resources [4, 5]. Although the power rate of microgrids is limited to a few MVA, it is relative to its application area and grid type. Power parks refer to interconnection of several microgrids that are installed to meet higher power demands where increased stability and control opportunities are necessary. Moreover, the interconnection of renewable sources and a microgrid contributes to decreased environmental emissions [3, 7].

In a macrogrid (conventional grid application), only one-third of the fossil fuel consumed is converted to electricity; the remainder is dissipated as heat energy. A microgrid, on the other hand, can communicate with consumers and thus manage demand and supply easily. About 5-7% power is lost along transmission lines in a macrogrid whereas, in a microgrid, all the power stays at the distribution level. Another projected point is that a 20% of generation capacity exists to meet peak demand of 5% time for utility grid where it has a “domino effect failure” can lead to a blackout. In North America, in 2003, more than a hundred power plants were forced to stop power generation due to the cascading effect of failing plants. One feature of a microgrid is independent operation during widespread failure or during fluctuation of power (intentionally or unintentionally), or even for cost-optimization purposes. In reality, microgrid has black start facility if it is required due to any sort of disaster [6-8].

This study will briefly describe the components, structure and types of microgrids. The paper presents an introduction to microgrids by assembling several comparisons, components, and control methods that are independently examined in current research. It is intended to lead the researcher to examine the real-world application of a microgrid, and provide insight for potential improvements. Additionally, the comparison of microgrids in several regions with varying parameters will allow a conclusion on the design requirements for a particular microgrid application scenario with specific, available resources. It also tabulates all necessary information about microgrids, and then proposes a standard microgrid for optimal power quality and maximized energy harvest. Finally, it focuses on removing knowledge gaps related to power systems in light of a future trend and potential improvements [1, 8, 9].

2. Overview of the Microgrid

Researchers are extensively studying microgrids in order to construct test beds and demonstration sites; the classification of microgrids and relevant key technologies should therefore, be addressed [1, 10, 11]. In this paper, we categorize microgrids into three types: facility microgrids, remote microgrids, and utility microgrids. The following characteristics are considered: their respective integration levels into the power utility grid; their impact on main utility providers; their different responsibilities and application areas; and their relevant key technologies. Facility microgrids and utility microgrids have utility connection modes while remote microgrids do not. Remote microgrids are located in highly dispersed consumption areas as compared to facility and utility microgrids. Facility microgrids can keep on operating in an intentional or an unintentional island mode. However, in every type of microgrid, the micro sources, loads, network parameters, and control topologies will vary [1,10,11].

First, a definition: “a microgrid is a localized group of electricity sources and loads that normally operate interconnected, and acts as a single controllable unit that is synchronous with the traditional centralized grid (macrogrid), but can disconnect and function autonomously as physical and/or economic conditions dictate” [12]. As shown in Fig. 1, a microgrid is made up of various renewable distributed generators, non-renewable distributed generators, energy storage devices, different types of microgrid loads, interfaced distributed energy resources (DER), interconnected microgrids, stability and control systems, and communication systems [4-5]. A point of common coupling (PCC) is the interconnection of a macrogrid and the distribution/generation side of a microgrid [39-44].

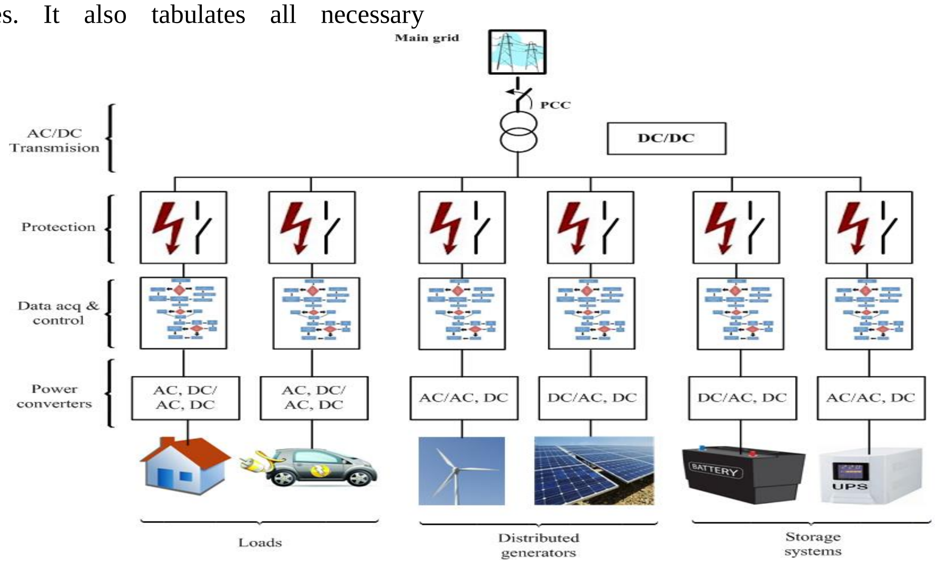

Fig. 1. Microgrid architecture

2.1. Distributed Generators

There are two different types of generation technologies applicable for microgrid design such as renewable distribution generation (solar thermal, photovoltaic (PV), wind, fuel cell, CHP, hydro, biomass, biogas, etc.), and non-renewable distribution generation (diesel engine, stream turbine, gas engine, induction and synchronous generators, etc.) [8]. The use of wind energy has rapidly increased all over the world by a rate of around 30% per year and has become a significant resource in microgrids, along with solar energy. These emerging technologies and well-established generation technologies are well known, and a detailed study of those generation systems is beyond the scope of this paper.

In Table 1, a summary of distributed generation technologies has been provided from a component can be selected that is based on plant design and system requirements, along with cost analysis information as shown in Table 2.

The power generation from renewable distribution generation is challenging, as they are intermittent power sources. The output power heavily depends on solar as almost every kind of renewable source is somehow related to a solar energy system. Thus, building a power system without any sort of non-renewable DGs is risky in term of reliability. According to a report of the Resnick Institute [13], more than 80% of the U.S. population, representing 37 states, have legislated renewable energy standards that involve up to 33% of energy estimated to be delivered to customers by 2020. In addition, about $675 billion will be invested in the U.S to set up distribution infrastructure by 2030. Consequently, each state has stepped up their target of standard distribution and generation as well as renewable energy generation. Many states have already started massive electrification initiatives as demand increases and reliability issues to grow.

Table 1. Summary of distributed generation technologies

Overview for Distributed Generation Technologies										
	Size Range (kW)	Efficiency(%) Electric	Efficiency(%) Overall	Emissions (g/kWh)	Foot print (sqft/kW)	Packaged Cost ($/kW)	Installation Cost ($/kW)	Electric- Cost-to-Gen. (cents/kWh)	Cogeneration Cost -to-Gen.(c/kWh)	Maintenance Costs (cents/kWh)
Reciprocating Engines										
Spark Ignition	30-5.000	31-42	80-89	Nox:0.7-42 CO:0.8-27	0.28-37	300-700	150-600	7.6-13.0	6.1-10.7	0.7-2.0
Diesel	30-5.000	26-43	85-90	Nox: 6-22 CO: 0.1-8	0.22-0.31	200-700	150-600	7.1-14.2	5.6-10.8	0.5-1.5
Dual Fuel	100-5.000	37-42	80-85	Nox: 2-12 CO: 2-7	0.15-0.25	250-550	150-450	7.4-10.7	6.0-9.1	
Turbines										
Microturbines Non-Recup	30-200	14-20	75-85	Nox: 9-125ppm CO: 9-125ppm	0.15-0.35	700-1.000	250-600	14.9-22.5	10.1-15.9	0.8-1.5
Microturbines Recup.		20-30	60-75		0.15-0.35	900-1.300		11.9-18.9	10.0-16.8	
Industrial Turbines	1.000-5.000	20-40	70-95	Nox: 25-200ppm CO: 7-200ppm	0.02-0.61	200-850	150-250	8.7-15.8	5.8-12.2	0.4-1.0
Fuel Cells										
PEM	5-10	36-50	50-75	Nox: 0.007 CO: 0.01	0.9	4.000-5.000	400-1.000	21.9-33.3	20.7-33.3	0.19-1.53
Phosphoric Acid	200	40	84	Nox: 0.007 CO: 0.01	0.9	3.000-4.000	360	18.6-22.8	17.0-21.2	
Renewable										
PV	5-5.000	NA	NA	NA	NA	5k-10k	150-300	18.0-36.3	N/A	0.3-0.7
Wind	5-1.000	NA	NA	NA	NA	1k-3.6k	500-4k	6.2-28.5	N/A	1.5-2.0

2.2. Energy Storage Devices

Energy storage is a vital factor in order to legitimize renewable energy resources as a reliable contributor to main sources and to provide a successful operation of microgrid. The energy storage process plays an important role in the balance between the generation of power and energy demanded [7, 13]. The requirements of energy storage components in a microgrid are listed below;

i. Balancing power demand between the generation side and the load side is the first priority for energy storage devices (since the sources are intermittent and transient disturbances lacks of inertia).
ii. Storage of maximum energy demands during off-peak hours and being able to supply all loads when required.
iii. To eliminate loaded parts from microgrid that helps to meet unpredicted and sudden demands.
iv. To provide smooth transient conditions from grid-tied to islanded operation or vice versa.

Table 2. Cost analysis for various type DGs technologies [14, 15]

US average levelized costs (2011 US Dolar/megawatthour) for plants entering service in 2018						
Plant type	Capacity factor (%)	Levelized capital cost	Fixed O&M	Variable O&M (including fuel)	Transmission investment	Total system levelized cost
Dispatchable Technologies						
Conventional Coal	85	65.7	4.1	29.2	1.2	100.1
Advanced Coal	85	84.4	6.8	30.7	1.2	123
Advanced Coal with CCS	85	88.4	8.8	37.2	1.2	135.5
Natural Gas-fired						
Conventional Combined Cycle	87	15.8	1.7	48.4	1.2	67.1
Advanced Combined Cycle	87	17.4	2	45	1.2	65.6
Advanced CC with CCS	87	34	4.1	54.1	1.2	93.4
Conventional Combustion Turbine	30	44.2	2.7	80	3.4	130.3
Advanced Combustion Turbine	30	30.4	2.6	68.2	3.4	104.6
Advanced Nuclear	90	83.4	11.6	12.3	1.1	108.4
Geothermal	92	76.2	12	0	1.4	89.6
Biomass	83	53.2	14.3	42.3	1.2	111
Non-Dispatchable Technologies						
Wind	34	70.3	13.1	0	3.2	86.6
Wind-Offshore	37	193.4	22.4	0	5.7	221.5
Solar PV	25	130.4	9.9	0	4	144.3
Solar Thermal	20	214.2	41.4	0	5.9	261.5
Hydro	52	78.1	4.1	6.1	2	90.3
U.S. Energy Information Administration, Annual Energy Outlook 2013, December 2012, DOE/EIA-0-383(2012)						

v. To accommodate the minute–hour peaks in the daily demand curve [16,17]

Energy storage technologies are mainly classified as electrochemical systems (usually batteries and flow cells), kinetic energy storage systems (flywheel energy storage) and potential energy storage (pumped hydro or compressed air storage) [16,18,19]. The summary of existing storage technologies is shown in Table 3. The batteries, flywheels and super capacitors are more suitable for microgrid application. Energy storage systems based on batteries constitute the best solution to ensure sustainability of fixed voltage and frequency operation while using renewable energy sources (RES) [8, 11, 16].

The alternative flywheel method is well suited as a central storage device due to its ability to absorb and release energy quickly. However, flywheel method remains too expensive for large-scale power system applications when used in an advanced design. In uninterruptible power supply applications, the storage systems compete with both batteries and flywheels with regard to high power demands, power density and efficiency [16]. Fuel cells or traditional generators with effectively large inertia could be another option for a microgrid storage system.

2.3. Microgrid Loads

A microgrid system has various kinds of load and it plays a vital role for its operation, stability and control. An electrical load can be categorized as a static or motor/electronic load. The microgrid can supply various kinds of loads (such as household or industrial) which are assumed to be sensitive or critical, and demand high-level reliability. This kind of operation requires several considerations such as priority to critical loads, power quality improvement supplied to specific loads, and enhancement of reliability for pre-specified load categories. Additionally, local generation prevents unexpected disturbances with fast and accurate protection systems [8,20,21].

The load classification is important to define the predicted operating strategy in a microgrid arrangement under the following considerations:

i. The load/source operation strategy required to meet the net active and reactive power in grid-tied mode, and stabilization of the voltage and frequency in island mode.
ii. improvement of power quality,
iii. reduction of maximum load to enhance the DER ratings,
iv. maintaining desired operation and control [7]

3. Distributed Energy Resources (DER) Interfaces

Power converters allow connection of independent equipment and components on a common system. Distributed generation (DGs) technologies require specific converters and power electronic interfaces that are used to convert the generated energy to suitable power types directly supplied to a grid or to consumers.

Table 3. Overview of existing storage technologies

	Technologies															
	PHES	CAES	Lead-acid	Ni-Cd	Ni-Mh	Li-Ion	NaS	Zebra	VRB	ZnBr	Metal-air Batt.	Flywheels	SMESb	Sup.Cap.	Fuel Cells	TES
Power Rating (MW)	100-5000	1-400	0.001-50	0-46	0.01 to ~MW	0.1-50	0.05-34	0.001-1	0.005-1.5	0.025-1	0.02-10	0.002-20	0.01-10	0.001-10	0.000001-50	0.1-300
Discharge Duration (h)	10-100	2-100	h	s-h	s-h	0.1-5	5-8	min-8h	s-8h	s-4h	3-4	s-15min	s	s	s-24+	1-24h+
Gravimetric Energy Density (Wh/kg)	0.5-1.5	30-60	30-50	50-75	30-110	75-250	150-240	100-140	10-75	60-85	110-3000	5-130	0.5-5	0.05-30	600-1200	80-250
Volumetric Energy Density (Wh/L)	0.5-1.5	3-6	50-80	60-150	140-435	200-600	150-240	150-280	15-33	30-60	500-10k	20-80	0.2-2.5	100000+	500-3k	50-500
Power Density (W/kg)			75-300	150-230	250-2k	100-5k	150-230	130-245		50-150		400-1600	500-2000	500-5000+	5-500	10-30c
Efficiency	70-87%	40-80%	70-92%	60-70%	60-66%	85-90%	75-90%	~90%	65-85%	75-80%	40-60%	80-99%	85-99%	97%+	20-70%	30-60%
Durability (years)	40-100	20-100	5-15 (~10)	5-20	3-15	5-20	15	8-14	10-20	5-20	-	15-20	20+	20+	5-15	10-40
Durability (cycles)	12k-30k+	30000+	500-1200	10002500	200-1500	100010k	20005k	25003k	13000+	~2000	100-300	1000000	10000+	100k+	100-10k	200014k
Capital Cost (kW/$)	600-2000	400-800	300-600	500-1500		12004k	10003k	150-300	600-1500	700-2500	100-250	250-350	200-300	100-300	10000+	200-300
Capital Cost (kWh/$)	5-100	2-50	200-400	800-1500		600-2500	300-500	100-200	150-1000	150-1k	10-60	10005k	1000-10k	300-2000	6000-20k	3-60
Tech.maturity level (1 = low, 5=high)	5	5	5	4	4	4	4	4	3	2	1	4	3	3	2	3-4
Availability	95%+	65-96%	100%	99%+	99%+	97%+	up to 99.98%	99.9%+	96-99%	94%	N/A	99.9%+	99.9%+	99.9%+	90%	90%

The development of an advanced power electronic interface (APEI) helps meet various power demands with lower cost compared to DER systems since power converters provide similar functions. Thus, the stability of the microgrid is maintained while source variety is also accommodated [21,22]. A typical block diagram of a DER power electronic system and the power electronics interface in a microgrid are shown in Fig. 2 and Fig. 3 respectively.

3.1. Function of Power Electronic Interface Module

DER refers to both DG (renewable and non-renewable) and energy storage technologies as well. Grid-tied inverters are required in most of the emerging DER technologies in order to convert the generated energy into grid-compatible AC power, capable of controlling the voltage and frequency of a microgrid through respective control interfaces. There are several functions of power electronics interface modules such as power conversion, power conditioning (PQ), protection of output interface & filters, DER and load control, ancillary services, and monitoring and control [8,23]. Power electronics are used to change the characteristics (voltage and current magnitude, phase and/or frequency) of electrical power to suit any particular application.

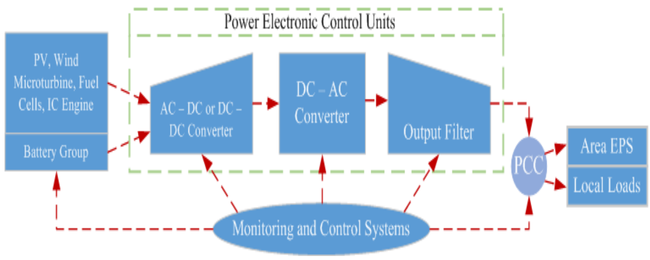

Fig.2. Power electronics of a typical DER system

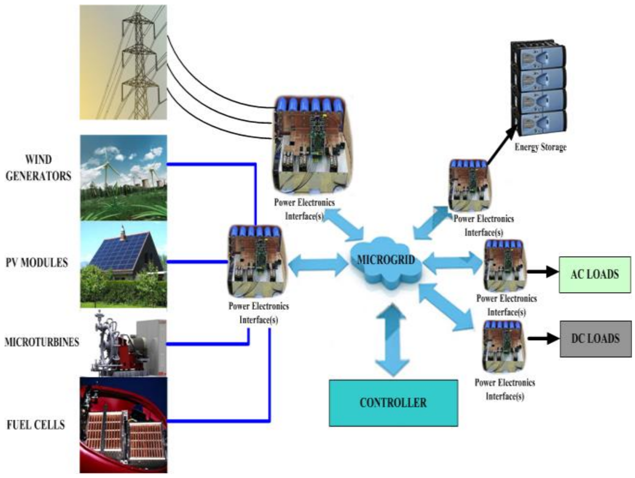

Fig. 3. Power electronics interface in a microgrid

It is an interdisciplinary technology. The bidirectional converters can be assumed the most widely used component of a microgrid among various power electronics interfaces due to their power-flow control ability. On the other hand, bidirectional converters can handle the generated power in a stable way during overload or no-load operation modes. A summary of numerous power electronics converters, characteristic interface configurations and methods of power flow control for DER has been provided in Table 4 and Table 5 respectively [24-27].

3.2. Interconnection of Microgrids

The operational philosophy is that the microgrid usually operates in grid-tied mode. In case of any disturbance occurs or maintenance planned in the utility, it may smoothly be disconnected from the utility at the PCC and continue to operate as an islanded and vice-versa. Microgrids usually connect at the distribution level with limited energy handling capability due to RES usages and heat wasting.

Since the rated peak power of a microgrid is typically limited to 10MVA, the interconnection relay that interfaces the microgrid and public service plays an important role, and the switching control method of this component determines the success of transition management through the grid [8, 28,29].

Table 4. Summary of power electronics conversion technologies

Power electronics systems for power conversion			
Power Conversion	Definition	Common Module Names	Application
AC-AC	These converters are used to adjust AC output voltage regarding to AC input voltage. The variable firing angle controls the output voltage of TRIAC. These type converters are known as AC voltage regulator	Cycloconverters, Hybrid Matrix Converters, Matrix Converters, Frequency Converter, Voltage Control Converters	Lighting /Heating Controls, Large Machine Drives, Voltage/Frequency level changer,
AC-DC	An AC to DC converter circuit can convert AC voltage into a DC voltage. The DC output voltage can be controlled by varying the firing angle of the thyristors. The AC input voltage could be a single phase or three phase.	Rectifier(Single or Three Phase, Half Bridge or Full Bridge)	DC Machine Drive, Energy Storage Systems, DGs Technologies interfacing, High Voltage DC (HVDC) Transmission
DC-AC	Variable AC output voltage, frequency & phase; and overall power handling, depending on the design of the specific device from DC input power	Inverter (Current Source Inverter, Voltage Source Inverter, Resonant Inverter)	AC Machine Drive, UPS, Induction Heating, Locomotive Traction, Static Var Generation, PV or Fuel Cell Interface with utility
DC-DC	These kinds of converters are used to adjust DC output voltage regarding to DC input voltage. The variable duty cycle controls the output voltage.	Boot Converters, Buck Converters, Buck-Boost Converters, Chopper, Cuk Converters	Power supplies for electronic equipment, Robotics, Automotive/Transportation, Switching power amplifiers, Photovoltaic systems
AC-DC-AC	AC/DC/AC converters, namely DC Link Converters, performs the conversion of AC input to AC output by using DC link between the stages (rectifier, DC link & inverter)	Back to Back Converter, Rectifier-Inverter Converters	For single or multiple applications of electrical machines, DGs application, Microgrid application

4. Stability, Control and Communication Strategies for Microgrid

Stability issues are more prevalent in microgrids than in large electric grids since the power and energy ratings are much lower, and the analysis of stability issues for AC microgrids follows the same concepts as in the main/macro grid. Both voltage and frequency need to be regulated through active and reactive power controls. If sources such as traditional generators with an AC output are directly connected without power electronic interfaces, stability is controlled through the torque and speed control of machine shaft. In DC microgrid systems, there are not any reactive power interactions, which seems to suggest that there are no stability issues. System control seems to be oriented toward frequency regulation only in a DC based microgrid.

Power quality is a major issue in microgrid systems as well as interconnection to DG systems. Power quality issues related to RESs, hydro, and diesel generators that are primary sources of DG systems are shown in Table 7 [5]. The stability of a microgrid is generally classified as one of two types. The first is frequency stability, including small signal and transient stability, while the other is voltage stability.

Table 5. Typical interface configurations and methods for power flow control [8,24]

Typical interface configurations and methods for power flow control for DER				
Primary Energy Source			Interfacing Technology	Power Flow Control
Distributed Generation	Conventional DG	Combined heat and power	Synchronous generator	AVR and Governor (+P, +/-Q)
		Internal combustion engine	Synchronous or induction generator	AVR and Governor (+P, +/-Q)
		Small hydro	Synchronous or induction generator	AVR and Governor (+P, +/-Q)
		Fixed speed wind turbine	Induction generator	Stall or pitch control of turbine (+P, -Q)
	Nonconventional DG	Variable speed wind turbine	Power electronic converter (AC-DC-AC)	Turbine speed and DC link voltage control (+P, +/-Q)
		Micro-turbine	Power electronic converter (AC-DC-AC)	Turbine speed and DC link voltage control (+P, +/-Q)
		Photovoltaic (PV)	Power electronic converter (DC-DC-AC)	Maximum power point tracking and DC link voltage controls (+P, +/-Q)
		Fuel cell	Power electronic converter (DC-DC-AC)	Maximum power point tracking and DC link voltage controls (+P, +/-Q)
Energy Storage	Long-Term Storage (DS)	Battery	Power electronic converter (DC-DC-AC)	State of charge and output voltage/frequency control (+/-P, +/-Q)
	Short-Term Storage (DS)	Fly-wheel	Power electronic converter (AC-DC-AC)	Speed control (+/-P, +/-Q)
		Super capacitor	Power electronic converter (DC-DC-AC)	Speed control (+/-P, +/-Q)

The analysis methods of small signal stability that are based on closed loop controllers are used to cope with problems of continuous load switching and managing the power demand of the micro-sources. Any fault occurring in one of the subsequent islands affects the microgrid in terms of transient stability. The stability problems in microgrid voltage are mostly produced by limited reactive power, load dynamics, and transient sources such as tap-changers. The stability on small signals can be enhanced by developing additional closed-loop controls, observers, and well-suited control strategies.

The transient stability is improved by using storage devices and adaptive protection devices. Furthermore, voltage regulators, reactive power compensators, load controllers, and current limiters assure the stability in a microgrid [10]. The control operation of a microgrid is required

i. to add or subtract new micro-sources without any modification of components present in the system,
ii. for selecting or optimizing operation point of a microgrid autonomously as well as manually,
iii. to connect or to isolate a microgrid from the main grid immediately and smoothly when demanded,
iv. for controlling active and reactive power independently,
v. for the correction of voltage sag and system imbalances,
vi. to meet the load dynamics involvement of a grid [4,10,30].

The current researches on microgrids are related to several issues such as independent control of each generator, improving the central controller, and agent-based observing strategies. The independent or namely self-governing control provides flexible adaptation of existing systems to variable conditions, and increased communication infrastructures can be integrated into the system easily. The agent-based observing system allows control of the microgrid remotely or locally in various levels. This method permits exploitation of the robustness of both centralized and distributed control systems [8,10].

Table.7 Power Quality issues related to DG systems

Power Quality Issues related to DG systems				
Power Quality Issues	Wind Energy	Solar Energy	Micro-hydro turbine	Diesel
Voltage sag/swell	✓	✗	✓	✓
Under/Over Voltage	✓	✗	✗	✓
Unblanced Voltage	✗	✓	✗	✗
Voltage Transient	✓	✗	✗	✗
Voltage Harmonics	✓	✓	✓	✗
Flicker	✓	✓	✗	✓
Current Harmonics	✓	✓	✓	✗
Interruption	✓	✓	✗	✗

4.1. Microgrid Control Strategy

A comparison of AC and DC microgrids are tabulated in Table 8.

There are several control techniques, which are stated below that help to manage the component level of a distribution system.

i. Master and slave control: master fixes the voltage and frequency values while the slaves control the current sources.
ii. Current and power flow control: this method controls the current and power distribution by using control signals.
iii. Droop control: this method is improved to combine with previous methods since the converters behave as non-ideal voltage sources [31].

Table 6. Overview of microgrid switch technologies

Microgrid Switch Summary								
Switching Technology	**DER Switch**	**Open/ Close Speed**	**Cost**	**Pros**	**Cons**	**Power Flow**	**Losses**	**Remarks**
Switchgear/ Circuit breaker	Circuit breaker based	20ms-100ms @60Hz	Low-med	>Additional protection not required	>Not suited for repeated open/close cycles	No	Negligible	Acceptable for the insensitive load
	Contactor based	20ms-100ms @60Hz	Low	>Rated for repeated open-close cycles >Lower cost, common	>Requires additional circuit breaker for fault current protection	No	Negligible	Switch has long and random response time
Static switch	SCR based	6ms-17ms @60Hz	Med-High	>Relatively low frequency switching with phase shift tech. >Can handle many open/close cycles	>SSR refuses to turn on when the inverter mode transfer the operation mode because the time of cross zero point may not occur >it cannot turn-on or turn-off synchronously in three-phase micro-grid system, because the phase difference of voltage and current	No	Significant	Relatively more noisy, Less efficient, bigger size/weight than IGBT
	IGBT based	10us-100us @60Hz	High	>High frequency switching with PWM technology >It can clamp the instantaneous currents and turn off in very short time frames	>Requires circuit breaker for fault current protection >Expensive and new technology	No	Significant	Most acceptable switch for microgrid to connect & disconnect public grid for double mode inverter
Power electronic interface	Converter based	10us-17ms @60Hz	Very High	>Most flexible, can handle AC/DC power >Real and reactive power flow can be controlled	>Response time depends on system dynamic performance >Additional circuit breaker may require and expensive	Yes	Significant	Provides the necessary adaptation functions to integrate all different microgrid components

Table 8. Analysis of control techniques in AC and DC microgrids [31,32].

Comparison of AC and DC microgrids in the control strategies aspects			
Mode	Controller	Microgrid type	
		AC	DC
Grid-tie	Microgrid Central Controller (MGCC)	- Monitoring is based on gathering data inherited from low voltage AC networks, DG systems, and loads. - provides several control methods: prediction, security observation, power flow control, and requirement management, - Maintains synchronized operation with grid and conserves power exchange at or before the contract points.	- The key function of the MGCC is controlling the power demand and voltage variations against changed conditions and loads, - Facilitates scheduling, observing loads, and Demand Side Management (DSM)
	DG Controllers (DGCs)	- Monitors and controls each DG unit in order to manage the load demand in both grid-tied and islanded modes, and controls the transitions through modes with the help of MGCC.	- assures transfer of all generated power by the DG to utility grid, and then can return to islanded mode safely when required.
Islanded	Microgrid Central Controller (MGCC)	- controls the power flow of DG (active and reactive), and stabilizes voltage and frequency, prevents interruptions by developing strategies and using management with ESS support. - Initializes local blackstart to maintain reliability of power supply and sustainability of service, - interconnects the microgrid to grid-tied mode when the utility grid is stabilized after a probable fault	- controls and stabilizes the power flow and load voltage when an error or change occurs in the load profile and distribution sections - picks up the generated voltage in grid-tied or islanded modes owing to MGCC features
	DG Controllers (DGCs)	- checks all DG units independently in order to assure that the generated voltage has been transferred to the load in islanded mode, and tracks the utility grid to operate in synchronized mode due to MGC features	- assists load sharing for each DG units in the islanded and grid-tied modes

4.1.1. Centralized control system

A centralized control system achieves intelligence from a particular central location, which depends on the network type, and could be a switch, a server, or a controller. It is easy to operate a centrally-controlled network as it presents increased control to the operator who maintains the entire system. This feature allows the manager to define broad control strategies in order to meet power requirements. However, the centralized control system requires a single control device that processes all measured data. This unique controller point could cause several communication problems, and it may lead to several faults that can shut down the entire system.

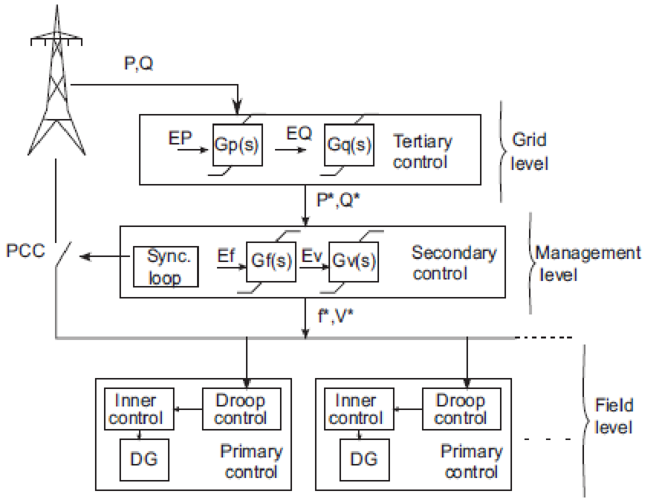

Fig. 4. Centralized hierarchical control of microgrids

4.1.2. Decentralized control systems

The decentralized controller enables a system where all devices are able to control themselves independently as opposed to a "master" controller. For instance, a decentralized controller can demand operation or not from a distribution point where such a solution increases the communication speed of the entire system. Conversely, completely decentralized systems also consolidate several problems. Since all decisions are produced at the distribution level, the manager may lose control ability and therein affect the entire microgrid. Such a drawback requires building a well-organized control system where the installation costs are higher than that of centralized controlled systems. Hence, selecting the type of control system for a microgrid becomes a trade-off among terms of cost. However, the best solution is known as the multi agent-based control system (MAS) that provides properties of both types of control systems. In order to perform a decentralized control, MAS was proposed by various researchers, and then numerous proposals have been developed on this concept. The independent structure of DER is based on this type of control and local controllers (LC) can be easily developed this way. These controllers can interact with each other to improve the communication infrastructure in a wide area where the voltage regulation is also provided by MAS [21,32,33].

4.1.3. Comparison of control methods

The MAS-based decentralized control presents several advantages among the others introduced above. The comparison criteria and results are seen in Table 9. Consequently, centralized control is assumed to be the most proper method when a defined operator operates the microgrid, and the generation and consumer sides of the system have agreed on similar expectations from the microgrid. This provides implementation of a practical management infrastructure, and installation costs are greatly reduced.

Nevertheless, decentralized control is best used in cases of various demands that are directed to the microgrid by the generation and consumption sides where the diversity of the sources and loads require real-time monitoring and adjustment. In this case, a centralized control could not meet the requirements. MAS-based systems are assumed to be the most economical solutions in these situations. Although the installation costs of MAS are higher than centralized control, the operation costs are greatly reduced and it can be amortized in a short time. Similarly, MAS control offers plug-and-play operation with the trade-off between costs and complexity of the controller. Analyses of classic droop control technique, local control technique and hierarchical control schemes of microgrids have been outlined below in Table 10, Table 11 and Table 12 respectively [21].

Table 9. Study on centralized and decentralized control techniques

Comparison of centralized control and decentralized control (MAS)		
Characteristic	Centralized	Agent-based control (MAS)
Power management	Better power management ability	Power management ability is good
Access of information	It is not possible to obtain all the data by MGCC	MAS provides each independent control with information about its neighbor
Data communication structure	A significant flow of data is required to produce similar results (Global & synchronous communication)	Localized network and data exchange is required for MAS communication (Local & asynchronous communication)
Real time functionalities	Difficult and expensive	Comparatively easy and inexpensive
Plug & play capability	MGCC must be programmed	Can be achieved without any modification in the controller
Configuration	Expensive	Cheap
Grid model	Global grid model	Local grid model
Efficiency	More efficient	Less efficient
Complexity of the control	Implementation of complex controllers is somewhat easier	Implementation of complex controllers is hard
Fault tolerance ability	Poor fault tolerance ability	Better fault tolerance ability
Flexibility & modularity	Reconnection is required for additional DERs	MAS able to install modular and scalable systems with high precision

Table 10. Analysis of classical droop control technique [19]

Properties of the classical droop method differences		
Advantage	Disadvantage	Possible Solution
Preventing the communications	Selecting just the voltage regulation or load sharing	Controlling the restoration periods, additional loops to obtain higher gain slopes
Higher flexibility	Lower harmonic elimination	Supplementary loops to control bandwidth, third harmonic injection, dynamic impedance adjustment, droop coefficients for harmonic elimination, several harmonic elimination strategies
Increased reliability	Inductance couplings	Dynamic impedance adjustment
Free laying	Impact of overall impedance	Supplementary loops to estimate the grid impedance, control of power flow,
Various power ratings	Lower response rate	Droop control for slopes, angle, adaptive decentralization, coupling filters; H∞ control
	Interconnection of RES	Droop control for nonlinear conditions and hybrid MPPT

Table 11. Analysis of a local control technique [21,34,35]

Local control operation and control methods		
Operation Type	Operation Mode	Control Method
Inner control of the DERs	➢ Controllable sources ➢ Renewable sources ➢ Long term storage/short term storage	➢ AVR and governor control ➢ Stall or pitch control of turbine ➢ Turbine speed and voltage controls ➢ MPPT and voltage controls ➢ State of charge and output, voltage/frequency controls ➢ State of charge, speed control
Power generation control	➢ Autonomous mode ➢ Grid connected mode	➢ Based on communications ➢ Droop methods ➢ Power export (with/without MPPT) ➢ Power dispatch, real and reactive power support
Islanding detection	➢ Active methods ➢ Passive methods ➢ Utility level methods	➢ Based on current injection ➢ Sandia National Laboratories algorithm ➢ Under/over voltage and under/over frequency algorithms ➢ Phase jump algorithms ➢ Based on communication signals ➢ SCADA

4.2. Communication Strategies Used in Microgrid

Suitable communication required to perform control and protection operations is one of the most important aspects of a microgrid. Microgrid communication systems used thus far in test beds are based on wireless communication methods such as Wi-Fi, WiMax, ZigBee, Global System for Mobile (GSM), and power-line communication. Contemporary microgrid research has used different communication protocols and researchers have been trying to generalize a standard communication protocol to reduce costs and speed up the development of microgrids. The communication system design should be performed considering the communication model and application protocol that are unique for microgrids.

Table 12. Analysis of a hierarchical control scheme of a microgrid [21, 31, 36, 37]

Hierarchical control scheme of a microgrid			
Aspects	Field/primary level control	Management/secondary level control	Grid/Tertiary level control
Objectives	➢ Inner control methods are used to meet the voltage and frequency requirement of DERs. ➢ Controls applied at source and load sides ➢ Generation control that assures performance in voltage and current modes, ➢ Islanding detection control that checks the operation mode for interconnection to utility grid.	➢ Minimize Area Control Error (ACE) that tracks frequency at a fixed value, maintains the power balance, maintains P and Q share among the generation units, ➢ Restoration control that is focused on tracking the desired voltage and frequency of the DG ➢ Interaction control through the DG sources and utility grid by using error minimization methods such as phase-locked loop (PLL) techniques. ➢ Optimisation methods that allow choice of operation type regarding generation and consumption	➢ Directing the operation of medium and low voltage (LV) ➢ Control based on Distribution network operator (DNO) interface ➢ Market operator (MOs)
AC microgrid control	➢ Primary control that depends on the droop control method regarding the various sources connected to DG ➢ Power sharing control based on the droop method ➢ The virtual impedance is an equivalent concept in applications. ➢ Combined both concepts such as P/Q sharing of sources, soft starting opportunities, and low voltage ride-through (LVRT).	➢ Avoiding the voltage and frequency deviation caused by first level control ➢ Only low bandwidth communication is required for this control level. ➢ Synchronization loop that controls the interconnection through the grid-tied and islanded modes.	➢ Power sharing control to the grid connection ➢ Tertiary control and synchronization control loops implementation. ➢ Reference generating for frequency and voltage values of the secondary level control. ➢ Park transformation for a general impedance case.
Islanding microgrids	➢ Synchronisation for grid-tied operation and variable V/f for islanded mode ➢ V/f control depending to the power sharing	➢ Frequency control, amplitude regulation, power quality improvements ➢ Energy management for load control, generator regulation for the consumption ➢ V/f restoration	➢ Interconnection of microgrids ➢ Interconnection of microgrids and utility grids.

The control processes in a microgrid should be performed by collaboration of several controllers at various levels such as distribution, microgrid, and unit where data acquisition and control signals are transmitted [5, 8, 38,39]. Microgrid communications systems should satisfy the following points:

i. Data exchange among all elements in the multi microgrid as well as within the microgrid

ii. Monitoring and data acquisition from all elements

iii. Must meet the demand of decentralized control for example hierarchical control

iv. Real-time generation and load shedding control, e.g. power management

v. Voltage and frequency control coordination

vi. Communication protocols must be employed for overall energy management, protection and control

vii. Must determine whether the microgrids can provide fast secondary services or not

5. Future of Grids

Today, the power industry faces many problems including the rising cost of energy, power quality and stability, an aging infrastructure, mass electrification, climate dynamics and so on. Those problems can be overcome using low-voltage distribution generation where all sources and loads are collocated. In Fig. 5, the application market of microgrids in 2022 is predicted where the majority of applications would be for campus-type microgrids. The projected microgrid market growth and the growth of microgrid revenue by region have been shown in Fig. 6 and Fig. 7 where North America holds the largest share. An estimation of microgrid growth follows as; [40-44].

i. The growth of globally-installed microgrid capacity has increased dramatically since 2011 and is forecasted to reach a total installed capacity of over 15GW by 2022.

ii. The market presents a potential of over $5billion and is likely to reach over $27 billion by 2022, in terms of market value for dealers

iii. At present, campus/institutional microgrids are the largest by application and is forecasted to grow at a compound annual growth rate (CAGR) of 18.83% from 2012-2022.

iv. Military, defense-based and commercial microgrids are forecasted to have a similar installed capacity by 2022.

v. Off-grid microgrids continue to grow at the highest CAGR for next 5-6 years, while the hybrid market is expected to grow at the highest CAGR during 2012-2022.

vi. A longer payback period requires for a completely developed microgrid.

There are many research opportunities still available before microgrids begin to play an important role in communities. Several vital issues have been explained below [41,42].

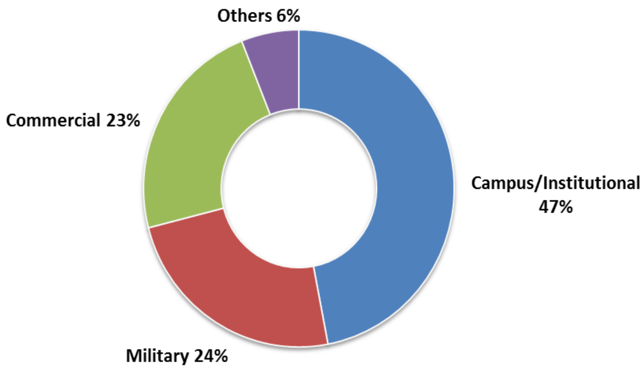

Fig. 5. Forecasted microgrid application market in 2022

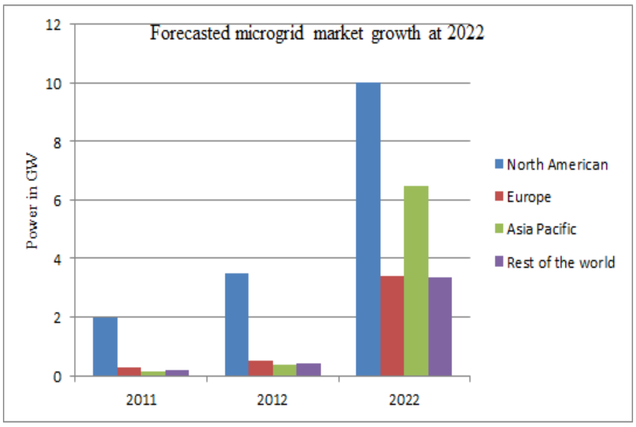

Fig. 6. Forecasted microgrid market growth in 2022

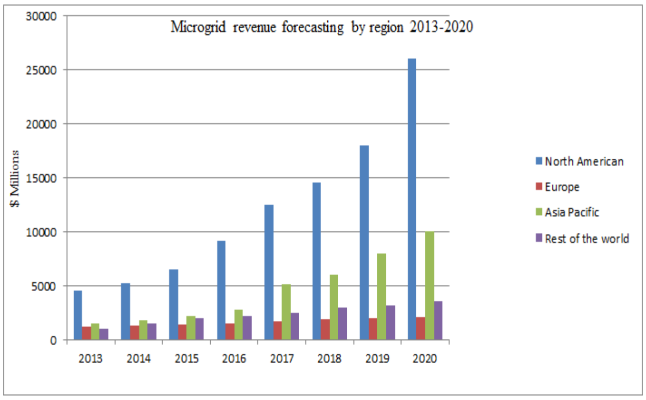

Fig. 7. Growth of microgrid revenue by region

i. Investigation of stability issues for both grid-tied and islanded mode for various types of microgrids, in term of voltage and frequency.

ii. Investigation of the full-scale development, and experimental evaluation of V/f control methods according to several operation modes.

iii. Determining the transition dynamics between grid-tied and islanded modes based on interactions between the distribution generation and high penetration of distributed generation.

iv. Definition of intelligent and robust energy delivery systems in the future by providing significant reliability and security benefits.

The future grid system needs to be changed to the more efficient use of available energy. Several features of prospective grids are given below;

i. Networked, loosely integrated independent microgrids
ii. Harnessed heat and power (CHP)
iii. Allowing demand response
iv. Avoidance of transmission losses
v. Integration of the RES
vi. Resilience to domino failures
vii. Empowerment of consumers and independent power producers to be proactive players and stakeholders in energy transactions
viii. Forecast of load and generation
ix. Introduction of several loads for inverter and converters
x. Introduction of distributed generation with DC output for numerous energy sources
xi. Requirements for higher quality power [43-47].

6. Commercial Planning of Microgrid

It is necessary to work on several issues to introduce a microgrid as a commercial product. Politically, a microgrid may not work because the local utility did not see the benefit of removing the macrogrid and replacing it with microgrids. It might take more time for microgrids to become primary agents of power supply. Besides, utility companies still have ownership over wires and transmission components. Permission from utilities is needed for transferring power through the macrogrid. Moreover, utility operators assume the microgrid as a competitor and they have started investing in the improved reliability of macrogrids.

Furthermore, the existing grid codes need to be changed to allow for consideration of microgrids. Localized power will help from a user/energy/environment point of view, but politically, utility companies do not see it that way. The state of the industry is going through a revolution and significant evaluation until pertinent matters have been addressed and decisions have been made. At present, utility companies are slow to embrace new technology but, unless they release ownership/control of equipment, microgrids will not be commercially viable. Still, more research is required to resolve several critical issues as well as provide encouragement and support for microgrids from suppliers to local and federal administrations.

7. Conclusion

This topic is currently being concerned by the alarms on global warming, pollution and carbon footprint emissions. Microgrid systems facilitate remote applications and allow access to pollution-free energy and gives impetus to the use of renewable sources of energy. Moreover, in an event of a power grid failure, a microgrid is one of the best alternatives. Renewable energy systems help to generate clean and sustainable energy as the demand for energy continues to rise. Nevertheless, there are several challenges that need to be tackled to facilitate the RES that could be used to complete prospective. Renewable resources are widely distributed and due to the intermittent nature of power, such a new distributed system can be provided by various generation approaches to obtain the maximum potential energy of the sources.

This survey paper has been dedicated to describe the microgrid term and the conceptual components are sketched for the different research fields. The possible research directions have been projected which are essential for future development of microgrid. Centralized and decentralized hierarchical controls of microgrids have been explained with the MAS decentralized control offers several advantages for example plug&play capability. The communication system, stability and control issues of microgrid have been presented. Finally, the possible feature of future microgrid has been illustrated with the growth of world distributed generation market.

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