# Microgrid Architectures and Control Strategies: A Review of Droop, Angle Droop, and Supplementary Control Methods

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**Abstract -** In this paper microgrid architecture and various converters control strategies are reviewed. Microgrid is defined as interconnected network of distributed energy resources, loads and energy storage systems. This emerging concept realizes the potential of distributed generators. AC microgrid interconnects various AC distributed generators like wind turbine and DC distributed generators like PV, fuel cell using inverter. While in DC microgrid output of an AC distributed generator must be converted to DC using rectifiers and DC distributed generator can be directly interconnected. Hybrid microgrid is the solution to avoid this multiple reverse conversions AC–DC–AC and DC– AC–DC that occur in the individual AC–DC microgrid. In hybrid microgrid all AC distributed generators will be connected in AC microgrid and DC distributed generators will be connected in DC microgrid. Interlinking converter is used for power balance in both microgrids, which transfer power from one microgrid to other if any microgrid is overloaded. At the end, review of interlinking converter control strategies is presented. document shows the required format and appearance of a manuscript prepared for IJSREM e-journals. The abstract should consist of a single paragraph containing no more than 200 words. It should be a summary of the paper and not an introduction. Because the abstract may be used in abstracting and indexing databases, it should be self-contained (i.e., no numerical references) and substantive in nature, presenting concisely the objectives, methodology used, results obtained, and their significance. A list of up to six keywords should immediately follow, with the keywords separated by commas and ending with a period.

***Key Words*:** Microgrid AC microgrid DC microgrid Hybrid microgrid Distributed generator (DG)

## 1.INTRODUCTION

### 1.1 Distributed Generators (DG)

Distributed Generators (DG) are playing a very important role in the current residential, commercial and industrial sectors of the power systems. Distributed generators provide an alternative to the present traditional electricity power generation sources i.e. oil, gas, coal & water. DG means a small scale power generation unit (1 KW– 50 MW) or informally one can say that the power generation units which are connected at distribution level nearer to load side [1]. The Distributed Energy Resources (DER) are becoming increasingly popular due to their high efficiency, low emission, and low noise levels [1]. DG can be used as Plug-andPlay approach [2]. In this approach, the unit can be placed at any point on the electrical system without any change of the controls. Distributed generator is a backup electric power generating unit that is used in many industries, departmental stores, hospitals, colleges, and commercial buildings. This back up unit is used to provide backup power during emergency times when grid power is unavailable. There are many distributed generator like Fuel Cell (FC), Micro Turbines (MT), Energy Storage Devices, Batteries, Flywheels, Super Capacitor. Some of the renewable energy resources like Photovoltaic (PV,) Wind Turbines (WT) are also included into distributed generation system.

Microgrid

A microgrid is a localized grouping of distributed energy resources, loads and energy storage devices that have the capability to operate in islanding and in grid connected mode [2]. Microgrid is growing rapidly because of its ability to integrate Distributed Generators (DG). The development of distributed generation (DG) has brought as many problems as it has solved for the distribution system. Main problem of the DG are related to stability and reliability of the distribution system. So, the interconnection of the distributed generators with the distribution system does not create a microgrid. But it must be well controlled with proper control strategies. This gives rise to the concept of local generation and local control of power in a distribution system that is further named as microgrid. Microgrids can improve performance, reduce cost and improve the efficiency of the power system [3]. Microgrid has many advantages such as:

1. Microgrid can provide high quality uninterrupted power supply to the consumers.
2. Microgrid improves the overall efficiency, stability and reliability of the power system.
3. Microgrid has ability to automatically isolate or reconnect itself with main grid during any grid disturbance.
4. Microgrid will provide power to the main grid at the time of surplus power generation in the microgrid.
5. It will help to reduce the $CO_2$ emissions by the optimal operation of distributed generation.

Microgrid can operate in two modes, islanded mode and grid connected mode [3].

(a) Islanded Mode: In islanded mode microgrid disconnects itself from the main grid and operates autonomously during the disturbances in the main grid. It will maintain high quality of power to the local loads.

(b) Grid Connected Mode: In grid connected mode, microgrid is connected to the main grid and enables bidirectional power flow.

The microgrid is known to operate while coordinating controlled generation and load that increase the robustness and reliability of the system, in both the modes of operation. The high penetration of distributed generators in microgrid has posed new technical challenges to the system. Some of the main problems in the microgrids are related to steady state and transient voltages and frequencies [4], protection [5], increase in short circuit levels and power quality problems during events like islanding, faults [6] and other disturbances to the system. After the development in microgrid technologies various microgrid architectures were introduced. So, in this paper various architectures of microgrids are reviewed. These architectures are discussed in following section with appropriate block diagram. There are mainly three architectures: AC microgrid, DC microgrid, hybrid AC– DC microgrid.

### 1.2 AC Microgrid

In AC microgrids, there are four major components that need to be coordinated, namely, control, i.e. active power, reactive power, harmonic, and unbalance components [7]. For the DC microgrids, there is only single component that has to be controlled i.e. DC power. These results in simplicity of the DC microgrid control system compared with the AC microgrid. Also power quality is main issue in AC microgrid compared to DC microgrid [7].

AC Microgrid Architecture

AC microgrid architecture is presented in Fig. 1. DC power from photovoltaic (PV) panel has to be converted into AC using DC–AC inverters before the connection [8]. To supply the power to DC loads, AC power has to be converted to DC. AC load can be directly connected with the AC bus. The embedded AC–DC converters are required for various appliances like computer, TV in home and office facilities to supply DC voltages. Wind power generation system is connected with the AC bus using converter that control active and reactive power. Main grid interconnection becomes easy because one has to simply match the grid and AC microgrid phase. The greatest benefit of an AC microgrid is that it can be easily stepped up for distribution over distance and again stepped down, near the load by using transformer with high efficiency [9]. Due to periodic zero voltage crossings, AC circuit protection schemes is benefited because fault current arc is extinguish by switching circuit breakers at zero crossing [9]. The stable voltage can be obtained by controlling reactive power independently from real power [9]. In grid connected mode, when main grid experiences an abnormal or faulty condition, then AC microgrid will isolate itself to

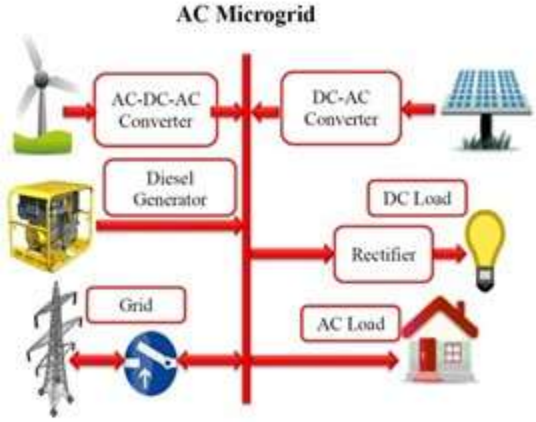


Fig. 1 AC microgrid architecture

protect the load within the microgrid. So, AC load within the AC microgrid will not be affected from main grid disturbance. Majority of the load in the present system is AC loads that can be directly interconnected with AC microgrid without any conversion. There are certain drawbacks of AC microgrid, such as for DC loads like computers, battery charging, DC fluorescent lamps, AC power must be converted to DC. Due to this conversion efficiency is reduced. While supplying power to the DC load with the power electronics converters, it will inject harmonics in the main grid. Another drawback of AC microgrid is that integration of the DC renewable sources is not easy because PV output is DC and it must be converted to the AC using inverter.

### 1.3 DC Microgrid

Currently research in the DC microgrid is gaining momentum due to development of renewable DC power generation sources, fluorescent lighting and their inherent advantage for DC loads in commercial, industrial and residential applications [9]. AC microgrids are already developed because of its various advantages that are listed earlier.

DC Microgrid Architecture

DC microgrid architecture [7, 10] is presented in Fig. 2. Two distributed generators are connected with the DC bus. For integration of wind turbine system with the DC microgrid AC–DC converter is required. Photovoltaic system is connected with DC microgrid via DC–DC boost converter.

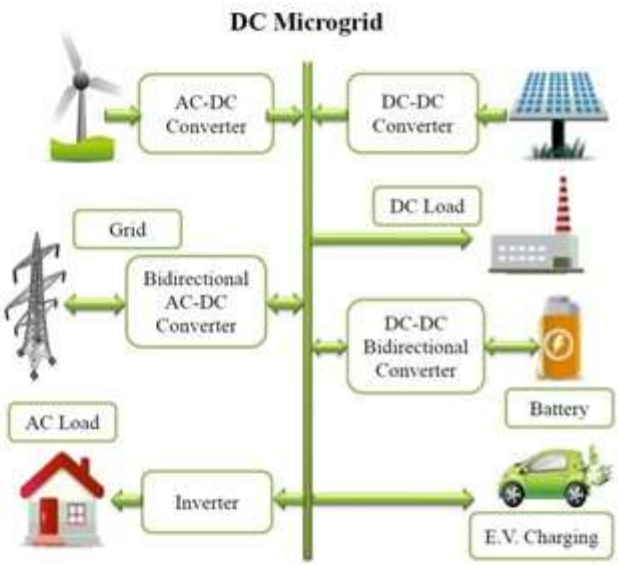


Fig. 2 DC microgrid architecture

This converter is used for the maximum power point tracking [5]. All DC load can be directly connected with the DC bus without any conversion, which increases efficiency and reduces cost of the power electronics converters. However, DC–AC inverters are required for conventional AC load connections. In many countries people are using electric battery operated vehicles. Charging of Electric Vehicle (E.V.) battery requires DC voltage. So, in DC microgrid electrical vehicle will be easily charged. In hybrid electrical vehicle charging new concept is introduced, that is, to feed power back into the grid during the night time. So, needy people can use that power during that time while vehicle is in garage. But this concept requires two directional metering. These things are not discussed here in detail due to different objective of this paper. The main advantage of the DC system is that one can directly connect battery storage system for backup power supply [10]. Backup storage system will provide power in the absence of any DG or during peak load period. It is also used to avoid supply interruptions in hospitals for critical equipments, in big office buildings for computers or in industries that required high quality power supply. Presently it is implemented with Uninterruptible Power Supply (UPS) with back to back conversion. A direct connection with DC microgrid eliminates power conversions and increases system efficiency.

There are certain benefits of DC microgrid like easy integration of renewable energy resources [10]. DC microgrid battery storage will continuously supply power to load during any power outages in the AC main grid [9, 10]. Increasing dependence on lighting technologies like compact fluorescent lamps could accompany DC distribution [1]. The operating cost and power converter loss of DC system can be reduced, because there is only a single AC main grid connected inverter unit is required. Although in DC microgrid separate DC distribution line is required, the cost performance of DC houses, information centers and hospitals are satisfactory. There are also some drawbacks of DC microgrid like limited power distribution up to a small short line length (km). Most of the loads in present power system require AC power. So, only DC distribution is not possible in current power system structure. Compared to AC system voltage transformation DC system is less efficient. For integration of AC distributed generators rectifier is required to convert AC power to DC power [11]. From the literature survey of microgrid architectures it can be concluded that individual AC or DC microgrid requires multiple reverse conversions for integration of various loads and renewable energy resources. This increases losses and complexity of the whole power system. The cost of the equipment is also increased due to the embedded AC/DC and DC/AC converters. A Hybrid AC–DC microgrid concept is introduced in the work of Wang et al. [12]. That avoids multiple reverse conversions in an individual Fig. 2 DC microgrid architecture AC–DC microgrid [13].

### 1.4 Hybrid AC–DC Microgrid

Hybrid AC–DC Microgrid Architecture Development of hybrid microgrid [12, 14] is initiated after reopening of discussion cum competition between George Westinghouse and Thomas Edison, which is related to merits of AC and DC distribution systems [9]. Relative merits of both AC and DC microgrid architecture are already discussed in this paper. Hybrid microgrid is the concept of combining both AC and DC microgrid architectures. So, hybrid microgrid is having advantages of both the individual microgrids [15]. A typical hybrid AC–DC microgrid is shown in Fig. 3. There are AC and DC microgrids that are connected together through bidirectional AC–DC (Interlinking) converters [12]. All DC power generators like photovoltaic (PV) panels and fuel cell (FC) are connected to DC microgrid through DC–DC boost converters [16, 17]. DC loads such as electric vehicles, fluorescent lamps are connected to DC microgrid through DC–DC buck converters. Energy storages devices are connected to DC microgrid through bidirectional DC–DC converters [14]. AC microgrid is usually tied up with utility grid. AC power generators such as wind turbine generators and small diesel generators are connected to AC network. AC loads such as AC motors are connected to AC microgrid. Voltage level of the AC grid is 230 or 400 V (L–L) rms. There are still no standard voltage levels for DC microgrid. When AC microgrid is overloaded at that time power will flow from the DC microgrid to AC microgrid [18]. In this case main converter will operate as inverter. When DC microgrid is overloaded then the main converter will operate as a rectifier and power will flow from AC microgrid to the DC microgrid.

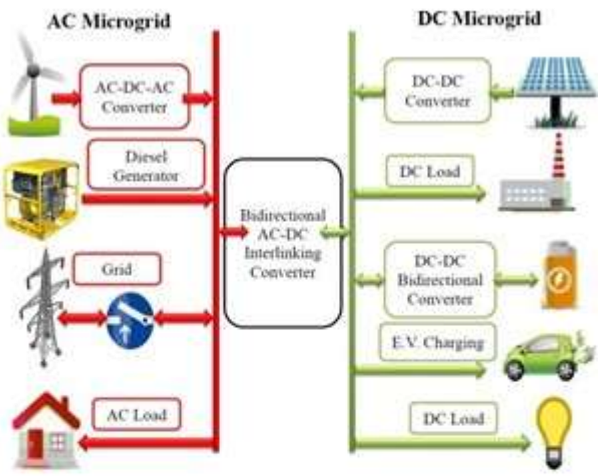

Fig. 3 Hybrid AC–DC microgrid architecture

Main function of the interlinking converter (IC) [19, 20] is smooth power transfer between microgrids. When both microgrids are overloaded during that time grid will supply power [21]. When both microgrids having surplus power generation then that surplus power will be fed into main grid [22, 23]. Hybrid AC–DC microgrid reduces process of multiple AC– DC–AC or DC–AC–DC conversions in an individual AC or DC microgrid [24] and provide high quality, uninterruptable and reliable energy supply to critical loads [25]. It also facilitates the connections of various renewable AC and DC sources and loads to the power system.

## 2. Control Strate gy

Droop control is widely used to regulate power sharing among parallel-connected distributed generation sources [26]. In the frequency droop control scheme, two droop characteristics are employed to determine the reference frequency and voltage magnitude based on the measured active and reactive power, respectively. The frequency droop control equations are expressed as follows:

$$f = f_0 - k_p (P - P\_ref)$$

$$V = V_0 - k\_q (Q - Q\_ref)$$

where f is the reference frequency, V is the reference voltage magnitude, $f_0$ and $V_0$ are the nominal frequency and voltage, P and Q represent the measured active and reactive power, P_ref and Q_ref are the corresponding reference values, and $k_p$ and k_q denote the active power–frequency and reactive power–voltage droop coefficients, respectively. These droop characteristics enable decentralized control and proportional power sharing among parallel sources without requiring communication links.

When active power demand increases frequency in microgrid will droop and when reactive power demand increases voltage will be drooped accordingly. So, as per droop characteristic of DG, it will supply power with drooped frequency & voltage. So, one can easily sense the active and reactive power shortage in the microgrid from the droop characteristics.

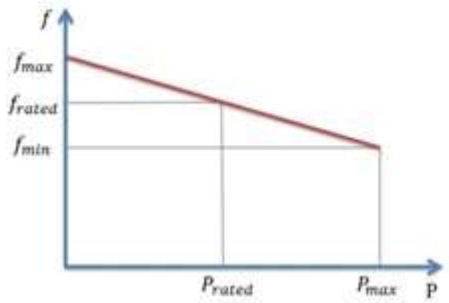


Fig. 4 Frequency versus active power droop characteristic

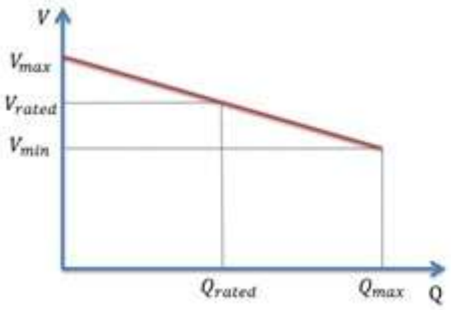


Fig. 5 Voltage versus reactive power droop characteristic

As per the active & reactive power demand, power generation of distributed generators will be increased. The main drawback of this method is that at higher droop gain there may be large power and frequency excursions during transients [26]. Angle Droop Control When all DGs are interfaced with converter in the microgrid an angle droop controller is more effective and responsive than a frequency droop controller [26].

## 3. Angle Droop Control

In this control strategy the real and reactive power is shared between the DGs and can be controlled by changing the voltage magnitude and its angle [26, 27].
between the DG and the microgrid. When the voltage source converter (VSC) output voltage is greater than microgrid voltage then reactive power will flow from VSC to microgrid and when the VSC output voltage angle is leading microgrid voltage then active power flows from VSC to microgrid. The control signals can be obtained
using following equations:
voltage magnitude and angle of each DG and Pi * , Qi * are the rated value of real and reactive power respectively. V and d are the actual measured value of voltage magnitude and its angle, when DG is supplying reactive power of Q and real power of P. The droop coefficients are m and n. The main drawback of this control strategy is that it requires communication channel for angle referencing [27]. If communication channel fails then it leads to out of phase condition and degrade the power sharing. Supplementary Control
In this control scheme lead-lag compensator [28] is used in order to maintain the system stability while using high droop gains to achieve a better load sharing. To maintain stability during power sharing it is desired to have low gain at high output power and high gain at low output power [28]. However, in case of low power (P) a constant high gain (droop coefficient m) magnifies the small signal oscillations in the output power that results in system instability [28]. At high frequency the phase leads, whereas at low frequency the phase lags. The amplified oscillatory component of the power signal consists of both lower and higher order harmonics of the base frequency (50 Hz). This results in variable phase in the signal. Therefore, a lead-lag compensator is implemented to provide an effective way to damp the oscillation and correct the phase while maintaining the system stability. The controller design is presented in the Fig. 7. As shown in Fig. 7 the Washout block captures the oscillations in the active power (DP). The oscillatory component serves as an input to the supplementary control block that generates (DEdrefi) to modulate the d component of the input signal to the ith converter.
Angle droop control is widely used in inverter-based microgrids to regulate active power sharing. Unlike conventional frequency droop control, angle droop directly modifies the phase angle of the inverter voltage as a function of active power deviation.
The fundamental angle droop control law is expressed as:
$\delta = \delta_0 - k_p (P - P\_ref)$
where δ is the inverter voltage phase angle, $\delta_0$ is the nominal angle reference, P is the measured active power, P_ref is the reference active power, and $k_p$ is the active power–angle droop coefficient.
For an inverter connected to the grid through a predominantly inductive line, the active and reactive power can be approximated as:
$P = (EV / X) \sin(\delta)$
$Q = (E / X) (E - V \cos \delta)$
For small angle variations, $\sin(\delta) \approx \delta$, and the active power equation simplifies to:
$P \approx (EV / X)\, \delta$
Using the linearized power equation, the angle can be directly related to active power as:
$\delta = (X / EV)\, P$
In closed-loop droop form, the control law becomes:
$\delta = \delta\_ref - k_p (P - P\_ref)$
The instantaneous angular frequency of the inverter is obtained as the time derivative of the phase angle:
$\omega = d\delta / dt$
Therefore, frequency variation is indirectly governed by active power dynamics in angle droop control.
Angle droop control is commonly combined with voltage droop control for reactive power regulation:
$E = E_0 - k\_q (Q - Q\_ref)$
where E is the inverter voltage magnitude, $E_0$ is the rated voltage, Q is the reactive power, Q_ref is the reference reactive power, and k_q is the voltage droop coefficient.
The dynamic behavior of angle and voltage droop control can be expressed as:
$d\delta/dt = -k_p (P - P\_ref)$
$dE/dt = -k\_q (Q - Q\_ref)$
The droop coefficients are selected based on maximum allowable deviations:
$k_p = \Delta\delta\_max / P\_max$
$k\_q = \Delta E\_max / Q\_max$
Typical design values include Δδ_max between 5° and 10°, and ΔE_max around 5% of rated voltage.
The complete set of governing equations for angle droop control is summarized as follows:
$\delta = \delta_0 - k_p (P - P\_ref)$
$E = E_0 - k\_q (Q - Q\_ref)$
$P \approx (EV / X)\, \delta$

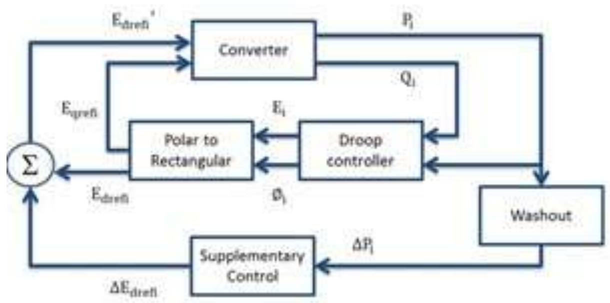


Fig. 7 Supplementary droop controller

Drawback of this control strategy is that complex parameter optimization method is required to determine the initial droop coefficient. Adaptive Control In this approach an adaptive droop control has been implemented, which is capable of changing the gain value with the change in load demand and the DG supply [18].

In angle droop control, active power sharing among inverter-based distributed generators is achieved by regulating the phase angle of the inverter output voltage instead of directly controlling the frequency. The angle droop law is expressed as $\delta = \delta_0 - k_p(P - P\_ref)$, where δ denotes the inverter voltage angle, P is the measured active power, P_ref is the reference power, and $k_p$ represents the active power–angle droop coefficient. For a predominantly inductive line, the active power transfer is given by $P = (EV/X) \sin \delta$, which can be approximated as $P \approx (EV/X)\, \delta$ for small angle deviations, establishing a linear relationship between power and phase angle. The inverter frequency is obtained from the time derivative of the voltage angle, $\omega = d\delta/dt$, enabling indirect frequency regulation through angle variation. To ensure proper reactive power sharing, angle droop control is typically combined with voltage droop control defined as $E = E_0 - k\_q(Q - Q\_ref)$, where E is the inverter voltage magnitude and k_q is the reactive power droop coefficient. These equations collectively form the basis of angle droop control for stable and efficient operation of inverter-based microgrid systems.

## 3. CONCLUSIONS

Different microgrid architectures and control strategies are presented in this paper. Out of all control strategies, some control strategies have already been tested in AC and DC microgrids by authors of cited papers. DC microgrid is in development stage due to development of renewable energy sources and energy storage devices. The main barrier to expand DC microgrid is lesser amount of DC loads in the present power system. Hybrid microgrid comes out to be a great solution with advantages of both AC and DC microgrid. Hybrid microgrid architecture reduces multiple reverse conversions that occur in an individual AC and DC microgrid. In hybrid microgrid development main focus of researchers is on the control strategy of interlinking converter for better power sharing between the two microgrids. A set of control strategies of microgrid is reviewed in this paper that can serve as a guide for implementation of robust stability control for a grid connected and islanded microgrid. In an islanded microgrid the main focus is on load sharing. Literature survey has been carried out to identify the most effective method for load sharing. For industrial application, traditional droop control is more reliable and does not require any communication channel. Angle droop control gives higher stability at higher gains compared to frequency droop, but it requires communication channel. For more accurate load sharing, supplementary control is used, which provides required damping of small oscillations with higher stability of the system, but simultaneous tuning of parameters for each controller makes it difficult to implement. Adaptive method achieves steady state quickly due to faster damping, but reference power values needs to be change every time when load changes. Control of ESS prevents voltage unbalance during power outage. Advanced load shedding maintains stable operation of critical loads under severe power shortage. All control strategies have relative advantage and disadvantage. As per the microgrid structure and critical loads, proper control strategy can be selected..

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