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REVIEW PAPER

A Review of Microgrid Architectures and Control Strategy

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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.

Keywords Microgrid · AC microgrid · DC microgrid · Hybrid microgrid · Distributed generator (DG)

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Introduction

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-and-Play 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.

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

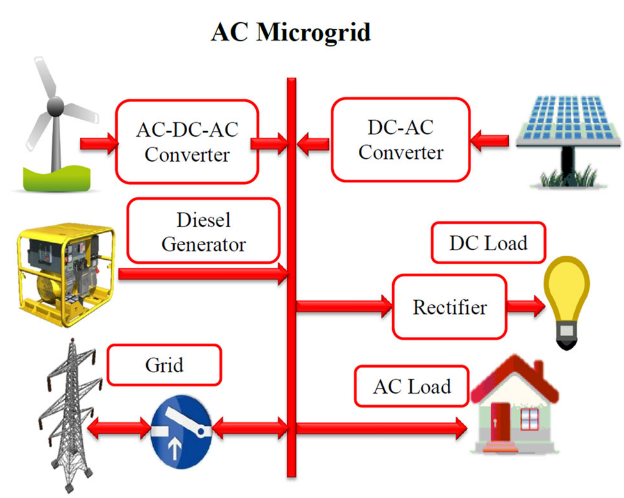

Fig. 1 AC microgrid architecture

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.

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. 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.

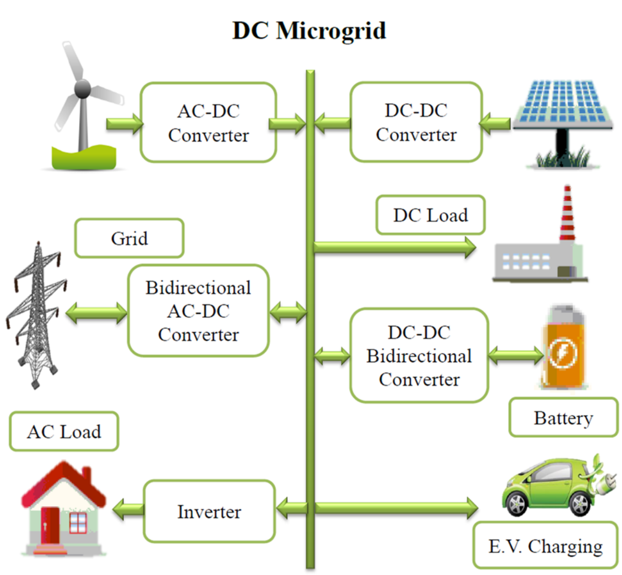

Fig. 2 DC microgrid architecture

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 AC–DC microgrid [13].

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. 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.

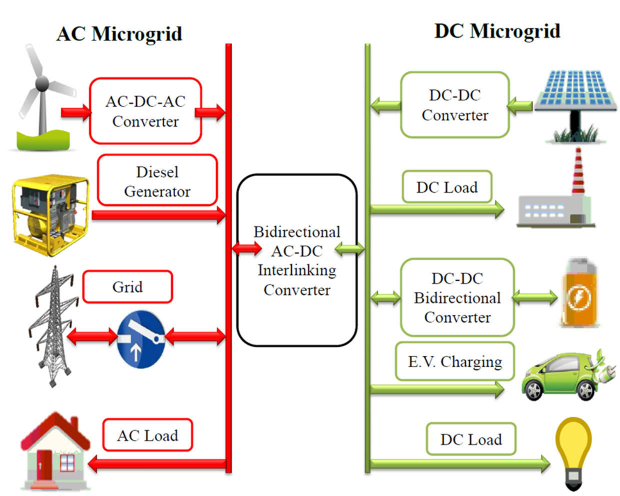

Fig. 3 Hybrid AC–DC microgrid architecture

Control Strategy

Frequency Droop Control

Droop control technique is used to control power sharing of two parallel sources [26]. In frequency droop control scheme two droop control equations are used to determine its reference frequency f and voltage amplitude V from its measured active power P and reactive power Q values, respectively. The frequency droop equations are as follow:

$$f_i = f_i^* - m_i \times (P_i - P_i^*) \quad (1)$$

$$V_i = V_{ri}^* - n_i \times (Q_i - Q_i^*) \quad (2)$$

where V_{ri}^* and f_i^* are the rated voltage magnitude and rated frequency. P_i^*, $Q_i^*$are the rated value of real and reactive power and P_i, Q_i are the measured real and reactive powers respectively. Here, m & n are the droop coefficients derived from the rated and maximum ratings of load. Figure 4 represents frequency vs. active power and Fig. 5 represents voltage vs. reactive power droop characteristic.

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. As per the active & reactive

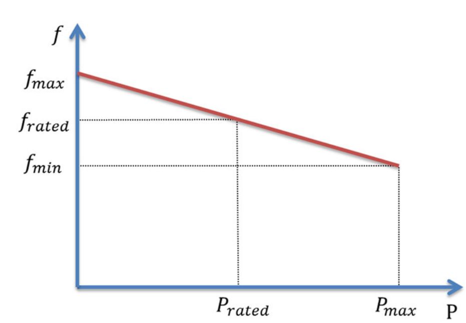

Fig. 4 Frequency versus active power droop characteristic

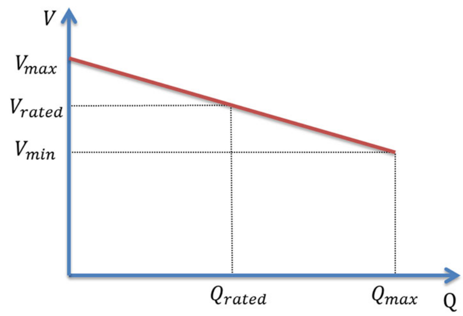

Fig. 5 Voltage versus reactive power droop characteristic

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]. 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].

Figure 6 represents typical interconnection 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:

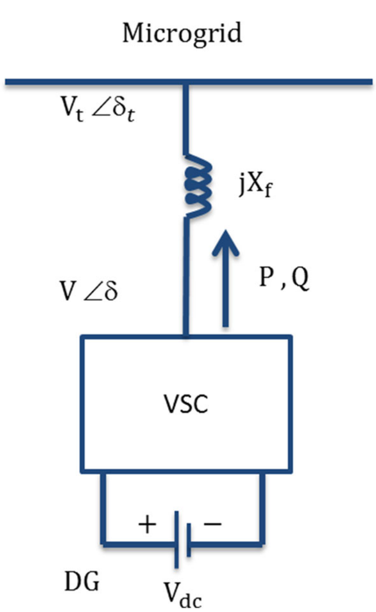

Fig. 6 Distributed generator connection in microgrid

$$\delta_i = \delta_i^* - m_i \times (P_i - P_i^*) \tag{3}$$

$$V_i = V_{ri}^* - n_i \times (Q_i - Q_i^*) \tag{4}$$

where V_{ri}^* and δi^* are the rated voltage magnitude and angle of each DG and P_i^*, Q_i^* are the rated value of real and reactive power respectively. V and δ 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 (ΔP). The oscillatory component serves as an input to the supplementary control block that generates (ΔE_{drefi}) to modulate the d component of the input signal to the i_{th} converter. The final voltage reference generated for the converter is expressed as:

$$E_i^* \angle \Phi_i^* = E_{drefi} + jE_{qrefi} \tag{5}$$

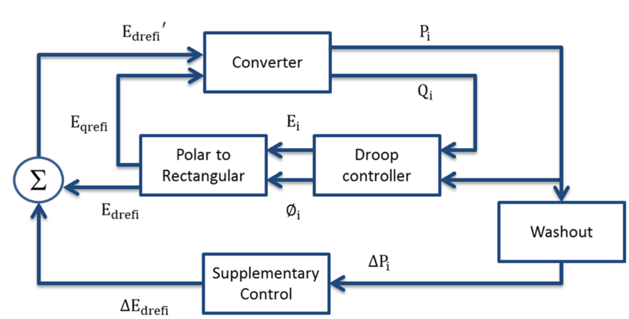

Fig. 7 Supplementary droop controller

Table 1 Comparison of various control strategy

Cases	Control strategy	Solutions	Drawbacks
Load and power sharing	Frequency droop control [26]	This control strategy is used for active power and reactive power sharing between different DG units of microgrid	Higher frequency deviation if droop gain setting is high
		Power sharing is achieved based on frequency droop characteristics and ratings of DG units. So, stress on any single unit can be eliminated	For higher droop gains an additional frequency restoration is required after transients
	Angle droop control [27]	Active power sharing with higher droop gain is possible, which improves stability of microgrid	Communication channel is needed for angle referencing. e.g. GPS
		As the frequency deviation is less it will achieve a stable power sharing operation under variable load condition	Communication channel loss for long period will create out of phase problems. This will lead to the degradation in power sharing
	Supplementary control [28]	This control strategy allows implementation of higher droop gains for better load sharing	Each converter requires separate controller
		It will damp out the small signal oscillation to a considerable extent	For parameter calculation complex parameter optimization method is required
			Simultaneous tuning of parameters for each controller is difficult
	Adaptive control [29]	This method achieves steady state quickly due to faster damping	Unable to achieve accurate power sharing due to low gain at high power
		As per the change in active power demand, droop gain will be changed accordingly	The reference power values need to be changed every time as load condition changes
Loss of distributed generator	Energy storage system [30]	It will provide spinning reserve for energy sources	System becomes more expensive due to large size energy storage
		Single Energy Storage System (ESS) with no communication channel provides an economic and reliable solution for voltage control	Unable to respond if voltage level changes, that might be lead to voltage collapse of whole system
			Maintenance is difficult with a single ESS
	Advance load shedding	This strategy will prevent complete blackout of the entire system during severe power outages	This method will create voltage difference between two different points in the system. This will lead to system instability
		In this method load shedding is used to maintain power balance in microgrid	Synchronous generator suffers from instability in this method
Excess generation	Battery charge control	Excess power is used to charge energy storage devices which can be used in islanding mode for backup power	Battery charging is restricted by its state of charge (SOC) limits. Charging beyond the SOC limits causes damage of the battery unit

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]. This control action is based on following equation:

$$m = (\Phi_0 - \Phi)/(P_0 - P) \qquad (6)$$

where P_0 is active power delivered at rated power angle ϕ_0. This deals with change in power supply by DG and change in load demand, with objective to keep system frequency (ω) within its safe limit. Therefore, a high value of droop coefficient is selected, when power supplied by DG goes below the rated power (P_0), whereas a low droop gain results in faster steady state where the load power demand is high. Droop coefficient value is obtained by comparing threshold active (P_{ithres}) and reactive power (Q_{ithres}), with the active (P_i) and reactive (Q_i) power outputs of the i_{th} DG unit. The logic can be stated as follows: When $P_i < P_{ithres}$, $m_i = m_{i0}$ and $P_i \geq P_{ithres}$, $m_i = m_{i1}$. Similarly, when $Q_i < Q_{ithres}$, $n_i = n_{i0}$ and $Q_i \geq Q_{ithres}$, $n_i = n_{i1}$, where the modified gains (m_{i1}, n_{i1}) are lesser than nominal gains (m_{i0}, n_{i0}). This method damps oscillations and helps to attain steady state faster (Table 1). However, this method degrades the accuracy of load sharing among the DGs [29].

Conclusion

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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