Trends in Islanded Microgrid Frequency Regulation – A Review
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ABSTRACT
With the growing concern for the environment and increasing power demand, utilizing renewable energy sources (RESs) in the form of microgrid clusters has become critically important and essential. However, there are associated challenges due to the intermittent nature of RESs from the viewpoint of reliable operation and control of the microgrids. Frequency control is one such most significant control issue. This paper has attempted a review of various methodologies and strategies for frequency control in microgrids and presented their classifications into different categories as per the available literature. The scope of this review includes exploration of many strategies for frequency control in microgrids such as demand response (DR) schemes, different control concepts, energy storage, optimization approaches/algorithms, effect of prosumers, smart homes, shiftable loads, emergency DR programs, electrical vehicle charging and discharging, heating ventilation and air conditioning systems, etc. The novelty of this review is in the categorization, the comprehensiveness, and outlining of future research directions for frequency control in microgrids.

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1. Introduction

Autonomic grids, at very microlevels, have been in existence for many decades in far flung areas, where the interconnection with the main power grid was not possible due to technical, geographical, and/or economic reasons. Therefore, owing to the scalability, cost competitiveness, and operational flexibility, conventional fossil fuel-based power generation has remained the only choice for supplying electricity to such locations. However, due to the adverse impact of the conventional power generation technologies on the environment, the world is moving toward greener generation technologies using renewable sources of energy. So, power generation using primarily the wind, solar, hydrogen, and small hydro plants and its integration with the existing grids/microgrids is a focus area research globally. However, there are many associated challenges that are yet to be addressed in order to successfully integrate renewable distributed energy resources (DERs). Some of these issues include [1-2]

(1) Scheduling the power generation units as per demand during uncertainties,
(2) Cost-effective and reliable operation of microgrids in the islanding mode during penetration of renewable generation,
(3) Designing of suitable demand side management (DSM) strategies,
(4) Proposition of new business models with emerging electricity market,
(5) Designing and development of improved voltage and frequency regulation techniques, and
(6) The design of control and marketing mechanisms in view of the evolving plug-and-play feature so as to facilitate for easy and flexible integration at any time.

The concept of microgrid [3] has emerged as one of the alternatives to utilize DER and facilitate their integration into integrated power systems. However, the research efforts are being made to address the issues therein with an objective of ensuring reliable, safe, and cost-effective operation of microgrids. Frequency control remains one of the significant control issues, which has drawn the attention of the researchers globally and hence, a lot of work has been reported in the literature and is being pursued as an active research area.

In the light of the above, this paper has attempted to present a comprehensive literature review on the frequency control issue in microgrids based on the available literature up to date. The review gives the recent perspective and is presented under different categories, probably not presented so far. The paper classifies the reported works for the frequency control in a systematic way and provides the volume of...
information in a very lucid manner. This paper, whose layout and flow can be understood from Figure 1, is structured into five major categories.

2. Concept of Microgrid

Microgrid concept came into being [4,5] as a reliable solution for the integration of DER along with energy storage systems (ESSs) and controllable loads. Such microgrid works as a single element for the main grid and responds as per appropriate control signals of the main grid. In technical forums, the microgrid definitions are still under discussion/research that define microgrid as a collection of small number of distributed generation units (DGU) with a coordination of ESS to produce reliable electricity to feed the controllable loads and interconnected with main grid through a static switch called point of common coupling (PCC).

Consortium for Electric Reliability Technology Solutions defines the microgrid concept as a forge-ahead way for the interconnection of unlimited DERs with main grid. Actually, the following two fundamental principles drive the microgrid concept:

- To derive the full advantage of integrated DER, in the form of a cluster – the microgrid, a system’s perspective is a must for utilities, society, and customers.
- The cost aspect is important from the business viewpoint and viability; therefore, these forge ahead concepts would become popular and widely acceptable only if these are cost-effective and meaningful [6].

Microgrid conceptual architecture is presented in Figure 2 [6]. Basically, it is a group of radial feeders that constitutes this architecture which further becomes a part of distribution system or electrical system network. For utility purpose, a single point of connection is used that is known as a PCC. As there are always some sensitive loads on the Feeders – A to C, as shown in the Figure 2, therefore, there is the need of local generation. None of the local generation is required for noncritical feeders. The PCC is used to disintegrate feeders A to C from the main grid within less than one cycle time, if required. In this architecture, four microsources are connected at nodes 8, 11, 16, and 22 that control the operation of the microgrid, utilizing the local current and voltage measurements.

In the case of any utility supply problem, a PCC opens and separates the sensitive loads from main grid while nonsensitive loads are still connected to target
load’s demand. During grid-connected mode, power generated from local generation is directly connected to nonsensitive loads. So, microgrid has an operating capability in both modes: grid-connected and islanding mode or keeping a transition in both modes [7,8]. In the grid-connected operational mode, power generated by microgrid is traded to main grid for maintaining power level while in islanding operational mode, reactive and real power generated are temporarily transferred to a storage unit that maintains proper balance with a local load. IEEE Standard 1547 defines guidelines for DER unit interconnections [9]. Microgrid islanding from the main grid can either be intentional in the case of scheduled maintenance/power quality degradation or unintentional in the case of contingencies/microgrid unscheduled events regarding safety of personnel/control strategy implementation changes. Microgrids without a PCC are known as isolated microgrids and implemented in remote areas, where main grid interconnection is not possible. As microgrid is a collaboration of renewable energy generation sources, control systems, demand response (DR) level, ESS that create a new requirement for automation and smart grid technology, so, for the proper management and control, an end-to-end control system must be in place to manage real-life assets [10].

3. Microgrid Frequency Regulation

It is the mismatch between the supply and demand of energy in microgrid that generates a deviation in frequency. In islanded mode of operation, generation (having an intermittent nature) and loads (demand based) are varying continuously, so frequency control plays an important role for system stability. The frequency and the rate of change of frequency, whose magnitude depends upon the imbalance size, provide instantaneous supply–demand gap information. Various control strategies have been put forth by many researchers that have attempted to minimize this deviation with the implementation of the battery ESS (BESS), superconducting magnetic energy storage (SMES), flywheel, priority load switching, dump load in the system, etc. [11].

3.1. Demand Response Algorithms/Methods

3.1.1. Demand Response Methods

In the implementation of microgrid, ancillary services play an important role for proper operation. The deep penetration of renewable energy source (RES) in power system makes the voltage/frequency regulation a challenging task that focused much attention on DR. It acts as an effective tool to make the balance between
demand and supply in real time as bidirectional communication and customer play an important role. DR provides low-cost, reliable, and system compatible alternative for a conventional spinning reserve that supports ancillary services [12]. A randomized DR algorithm, as proposed in Ref. [13], utilized frequency recovery time, smart appliances response, and frequency overshoot time, as the key factors in designing the algorithm to stabilize the system frequency. A microgrid is a cluster of DER with loads that provide an efficient DSM that has drawn the attention of the researchers worldwide [14]. In Ref. [15], agent-dependent new energy management system (EMS) is presented that provides power trading and customers’ participation in microgrid DR. Using Java agent development framework, the DR is made multiagent-based which suppresses the system peak and increases cost benefits to the customer. Developments of advanced Microgrid load management functionalities are presented in Ref. [16] which increase the microgrid resilience in standby microgrid mode, while considering microgrid energy storage (ES) capacity and frequency response. A demand management system is proposed in Ref. [17] that manages all consumers’ storage units, based on system and climate conditions, and also the controllable loads. It categorized the loads as critical, deferrable, and priority loads and considered environmental conditions like temperature, lumens, and water level to maintain the system frequency. A DR based on customer reward scheme was proposed in Ref. [18] for household consumers that deployed hierarchical control method at two levels having a primary controller for voltage regulation and a secondary controller that prevents the transformer from overloading. A new mechanism of DR is proposed in Ref. [19] for controlling thermostatic devices called Grid Explicit Congestion Notification that provides ancillary services to the grid without affecting the end users and supports in case of grid disturbances, while also controlling the voltage deviation of distribution networks. An active controller is proposed in Ref. [20] that improves the reliability of microgrid and minimizes the overall cost of simulated microgrid by managing its power consumption, minimizing purchased power quantity from distributed grid, increasing distributed grid sold power, increasing renewable generator size, and making a reduction in nonlinearity load. Combination of power electronics devices and optimization techniques is used in Ref. [21] that develops optimization-based DR for DC distribution networks that provide maximum efficiency of distributed and renewable resources. A cooperatively distributed algorithm incremental welfare consensus is proposed in Ref. [22] that solves the energy management issues in a smart grid having a number of distributed generation (DG) sources and critical load. It does not require central management unit for its operation and does not consider voltage deviations, line losses, and power flow dynamics of physical networks. To access the behavioral regularity of domestic loads, an algorithm is proposed in Ref. [23] in which an automatic meter reading is used in conjunction with detection algorithm. As wind power integrated power system is suffering from uncertainties, a new DR scheme of a forward market is proposed in Ref. [24] that permits any DR program to reach its full energy potential that improves the load profile and also balances the error in wind power forecast. A narrative DR model with built in centralized cost minimization is proposed in Ref. [25] that requires only consumer daily consumption information and avoids the investigation of price elasticity of demand forecast. A constraint satisfaction problem-based power flow management control method is presented in Ref. [26] that manages DG and DR at the same time and also presents a hybrid approach for maintaining network thermal limits and also has a capability to benefit distributed network operator planning and operational events for smart grid development. A stochastic differential game model is developed in Ref. [27] for autonomous DR, when price range of electricity changes for day hours and explains how end users can decrease their electricity bill as per load economics equations. Comparative analysis of the merits and demerits of DR algorithms/methods is given in Table 1.

3.1.2. Prosumers

In the evolving scenario of smart grid, participation of the user in the production of renewable energy that is further shared with other users connected to the grid has made the consumer a prosumer [28]. Therefore, prosumers not only consume energy but also play active role in sharing generated energy with another connected user in a grid thus, contributing to meeting the energy demand and thereby contributing in the frequency regulation [29]. Many researchers have put forth prosumer-based models addressing different issues including frequency regulation [28,30–37]. These propositions are around the concepts of energy management, DR, knowledge base management, community management, etc.

3.1.3. Smart Home

In a smart home, all the connected digital devices and mechanical elements are linked with an interconnected network so that all the devices can communicate with each other and interactive space is also created for the consumer [38]. Nowadays, modern smart technologies
monitor energy usage at the household level and a consumer can control home appliances with communication technologies either in direct or bidirectional modes. So, this results in lower disturbances in the load, minimum line losses, reduced network dynamics, good stability, and low operational cost besides meeting the demand quickly [39] and thereby positively impacting the frequency regulation as well. Different propositions and works have been reported in literature around the concept of smart homes [40–48]. Some of the integrated software of application and technological devices that make better interaction between home appliances and customers are (1) home EMS [44,49–51], (2) home automation [52,53], (3) integrated wireless technology [54–57], and (4) smart home microcomputers [58].

### 3.1.4. Demand Response

As proposed in Ref. [59], the energy should be saved by its rationalization to its consumptions, and this is possible only with a combination of DR program and advanced DG technologies in which management of resources becomes important with the developed framework perspective. From a research perspective, some of the authors have proposed new works considering various aspects including frequency regulation [60–89]. Different categories of consumers have been considered in some of these propositions of DR programs such as Residential User [70,71]; Commercial Users [68,69]; Services like Electric vehicle recharge [61,72,83], System reliability [60,87], Photovoltaic energy quality [86]; Market associated with DR programs [84,85,89]; and Distributed Generation associated with DR programs [73–82,88].

#### 3.1.5. Emergency Demand Response Programs

Emergency demand response programs (EDRPs) are the widespread programs which are voluntary in nature and provide economic benefits to the participants by incentivizing the consumption of electricity through linking it with the variable prices w.r.t. the time of use and/or when the reliability of the system is at risk. The end users are classified in various categories and made a part of the grid management by way of EDRPs. Many researchers have investigated on the impact of EDRPs on frequency regulation besides other ancillary services and lot of work has been reported in this area [90–101] to counter the adverse impact of intermittency of RESs.

#### 3.1.6. EDRP with Smart Home

The EDRP comes in effect when power generation is in shortfall. The EDR programs’ participants include data center, building, and energy consumers. Energy management for both the building and data center has attracted considerable attention in recent years. A lot of approaches have been developed and implemented around the idea of simple ON/OFF of the servers for energy proportionality to brown energy reduction to

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**Table 1. Comparison of different demand response algorithms/methods.**

| Reference | Advantages | Limitations |
|-----------|------------|-------------|
| [12]      | Provides frequency as well as voltage regulation with the minimization of manipulated responsive load amount during absence/presence of wind power generation | Regulates the system frequency to delay of 300 ms and becomes unstable beyond this time |
| [13]      | Considers all frequency dynamics such as frequency overshoot time, smart appliances response, frequency recovery time for designing the control algorithm | Its analytical results are validated only for IEEE 9-Bus test system Its economic viability needs more investigation |
| [14]      | Provides an efficient demand-side management | It offers the best price to maximize the benefits, but if customer offers high price, their DR contracts may not be scheduled by the microgrid aggregator |
| [16]      | Increases the microgrid resilience Mitigation of responsive loads as per frequency regulation | Supports the islanding operation only for shorter duration |
| [17]      | Manages all consumers’ storage units based on system and climate conditions | Environmental condition-based system |
| [18]      | Hierarchical control at two levels is used in which primary controller maintains the voltage regulation and a secondary controller prevents the transformer from overloading | Requirement of decision matrix for load adjustment |
| [20]      | Minimize the overall cost of simulated microgrid by managing its power consumption Minimize purchased power quantity from distributed grid Increases distributed grid sold power Increases renewable generator size | Minimization of overall cost depends upon heating and cooling system |
| [22]      | Solves energy management issues in smart grid Central management unit is not required for its operation | Power flow dynamics, voltage deviation, and line losses are not considered |
| [24]      | Permits the demand response program to use its energy potential to improve load profile Error balancing in wind power forecasting | Time frame and prices of the forward market are optimized in two stages and need to be updated in midterm and every round |
| [27]      | Described the load economics equations to reduce end user electricity bill | Shows a variation of both battery level and indoor temperature that are correlated to the changes in price values |

DR: Demand response.
cooling-aware scheduling to geographic load balancing aiming at exploiting location diversities for cost saving [102–121] and all these focused on energy management of the buildings/smart homes with a larger objective of frequency regulation.

### 3.1.7. EDRP with Electric Vehicle

Implementation of the EDRP at demand side is a good alternative solution for restoring grid frequency at the nominal level. For the realization of the DR, a commonly adopted approach is to control the discharging/charging rates of electrical vehicles (EVs) connected with the grid, which facilitates the grid operators for achieving various targeted objectives. Many investigations have been carried out by researchers on the use of EDRPs for EVs charging/discharging, scheduling, and other issues with one of the objectives as frequency regulation under varying operating conditions including any emergent contingency [122–137].

### 3.2. Control Strategies/Schemes/Methods/Techniques

#### 3.2.1. Conventional Control Strategies

As the interconnection of power system expands over the large geographical region, purely centralized or decentralized control approaches are not possible due to some computational and communication reasons. A compromise is reached that result in the emergence of hierarchical control scheme which is having three control levels: primary level, secondary level, and tertiary level and all these levels differ w.r.t. infrastructure, response time, and time intervals. Hierarchical control scheme is much beneficial for microgrid due to its controllable resources/loads and from the performance perspective also [138–141]. Microgrid has deep integration of DER unit that increases the number of operational challenges from the protection point of view and reliability perspective. For the past some decades, researchers are continuously trying to design a load frequency controller that is compatible with these challenges [142]. A novel control scheme is proposed in Ref. [143] that is fully capable of maintaining the balance of active power in voltage source converter (VSC)-based microgrid in islanding mode that regulates the DC voltage of distributed generators based on VSC within a permissible range without using communication link in an ESS and also maintains the microgrid small signal stability (SSS). A unified control strategy is proposed in Ref. [144] that enables the DER with microgrid, without considering its mode of operation, by taking the advantage of droop method and active feedback compensation, as it becomes a part of dispatchable system. A reliable control scheme with modified stability for both modes of operation of microgrid is presented in Ref. [145] with the help of Adaptive Backstepping method in which converter controller is augmented with microgrid stabilizer for system stability for the whole time duration without the need of communication and has suppressed transients. An improved control scheme is presented in Ref. [146] that makes the photovoltaic (PV) capable to adjust the active power for frequency regulation in case of faulty events and similarly, it works like a synchronous generator. A disseminate secondary control method is proposed in Ref. [147] which works on voltage restoration that also converges all distributed agent voltages into a single finite time reference value and considers some control input constraints for consensus-based frequency restoration that restores the frequency reference values and voltage with sufficient spacing of real power during load stability condition. An islanded inverter-based microgrid frequency regulation scheme is proposed in Ref. [148] that restores the frequency by using multistep load shedding scheme, besides secondary control limitations, as sensitive loads require high power quality. A coordinated operation of fast-responding inverter-based DERs with the slow-acting gensets is proposed in Ref. [149] in which load burden is redistributed between the different DERs for the frequency regulation. Doubly-Fed Induction Generator power control method is proposed in Ref. [150] that makes a participation in frequency regulation of microgrid which makes considerable reduction in frequency deviation dynamics and provides a rapid response with frequency variation. A hierarchical frequency control scheme is proposed in Ref. [151] for microgrid islanded mode that keeps the frequency stability of the islanded microgrid while having a good performance and robustness even considering the communication delays. In [152], an algebraic-type virtual synchronous generator is used to investigate the voltage/frequency deviation impact in microgrids which reduces the minimal number of parameters to reduce the voltage and frequency deviation autonomously. A sensor-based fault tolerant control scheme is proposed in Ref. [153] for electronically coupled DER units in grid connected mode of microgrid and develops a fault-dependent dynamical model for the DERs unit. Cyber attack is also shown in this scheme with a combination of sliding mode observer that behaves inherent robustness. A frequency-sensitive-based virtual inertia control techniques are discussed in Ref. [154] that extract the kinetic energy of the wind turbine and stored energy from the DC-link capacitor for short-term frequency regulation. Two control schemes are also proposed on the basis of modulating the inertia gains, one is a dynamic equation-based scheme and another is an
adaptive fuzzy-based scheme. It modulates the gains of inertia controls dynamically for a wide range of wind speeds on the perspectives of wind turbine stability and frequency security. It explores the analysis of frequency-sensitive-based virtual inertia controls (i.e. kinetic energy and DC-link capacitor) of variable speed wind turbine generators (WTGs).

### 3.2.2. Intelligent Control Strategies

Due to the limitations of conventional control strategies, artificial intelligent systems are used as alternatives to improve the power system capability [155]. The expert system or knowledge-based systems perform very well and its application in the electrical systems became an emerging trend [156]. A nonlinear artificial neural network controller was proposed in Ref. [157] that is based on the rate of change of frequency for electric load perturbation. Fuzzy logic control is much convenient system than classical control system and deals with nonlinearities by changing its parameters that work closely like human thinking and implements linguistic results into real value by fuzzy logic rules [158]. To mitigate power quality disturbance completely, a fast performance-based neural scheme is proposed in Ref. [159] for the extraction of voltage and a current component that uses instantaneous power theory and its results are further learned by an adaptive neural network. A combination of radial basis function network and multilayer perceptron with back propagation learning algorithm designs a new pitch controller in Ref. [160] for a variable speed wind turbine (VSWT) that adjusts performance coefficient (Cp) and tip speed ratio (Tsr) and also presents a blade pitch position control for the rated wind speed. A modified adaptive controller, with an enhanced feedback error learning approaches, is presented in Ref. [161] that has a supervised controller for asymptotic stability of the system and radial basis function neural network that are implemented in feedforward path to resist the power system variations on stability for making an improvement in system performance to a greater extent. A new online intelligent approach is presented in Ref. [162] that uses the combination of particle swarm optimization (PSO) and fuzzy logic for the optimal tuning of proportional integral derivative (PID) controller in the event of abrupt load changes, in the presence of nonlinearities and disturbance in which PSO improves the fuzzy membership function to make PID controller optimal. A generalized droop control (GDC) synthesis with adaptive neural fuzzy infrastructure system combination is presented in Ref. [163] for islanded microgrid that mitigates the dependency of microgrid on the online parameter and regulates the dynamic behavior of GDC that performs well in load variation. Neural network (NN)-based schemes are reviewed in Ref. [164] that are applied for control and monitoring of power system and it was proved that NN is best among these schemes. A new reconstruction algorithm is presented in Ref. [165] that is having an extraction of time-frequency components in which autoregressive model is used for low-frequency components while the back propagation neural network is used for high-frequency components that makes it much effective and promising. An interval type-2 fuzzy PID (IT2FPID) controller is presented in Ref. [166] for power system load frequency control in combination with Big Bang–Big Crunch algorithm that further optimizes membership functions of fuzzy and provides less overshoot, good settling time, and robustness during load disturbance. An isolated hybrid DG power system is studied in Ref. [167] that uses fuzzy PID controller with SMES to minimize the frequency and power deviation and also used Quasi Opposition Harmony Search algorithm that finds the global optimal solution of power optimization task. The fundamentals of the fuzzy potential function are used in Ref. [168] to define the potential function of every DER that is further minimized by gradient decent method for the determination of each DER unit set point at microgrid secondary level control. A robust energy management system (REMS) was proposed in Ref. [169] inside the model predictive controller (MPC) framework, in which an fuzzy prediction interval model is used as an available non-conventional energy sources prediction model in microgrid, so, resulting REMS is used as a real microgrid implementation for wind-diesel microgrid that works as a main source of uncertainty. A power electronics interface, that is having inverter and ES module, is presented in Ref. [170] for the distributed resources coupling with microgrid and regulates the micro source power rate, surge module power, maintaining power quality performances that regulate the output generator power. A novel synthesized control method is presented in Ref. [171] using a radial basis function fuzzy neural network for nonlinear systems that makes a parameter adjustment mechanism for frequency error detection and performs well during system parameter disturbances. A communication-based directional overcurrent relays with the dual setting is proposed in Ref. [172] for the microgrid protection in both modes either in islanded or grid connected and solves the infeasibility problem without current limiters, reduces operating time of relay, and maintains the proper protection coordination in between the relays. The EMS is proposed in Ref. [173] that considers the fuzzy-based control for selecting the better operational mode, unit commitment oriented microgrid, demand management actions considering the renewable power, and loads for the short-term forecasting. Comparative analysis of the merits and
demerits of control strategies/schemes/methods/techniques is given in Table 2.

### Table 2. Comparison of different control strategies/schemes/methods/techniques.

| Reference | Advantages                                                                 | Limitations                                      |
|-----------|-----------------------------------------------------------------------------|--------------------------------------------------|
| [149]     | (i) Unequal transient load sharing between inverters and inverter-based DERS are redistributed to prevent the system collapse and achieve better frequency regulation        | (i) Due to large transient loading DER susceptible to be collapsed that bring down the entire system |
| [150]     | (i) For the power sag problem, it reserves (doubly-fed induction generator/DFIG power margin up to 10%) that makes a support to microgrid frequency | (i) During disturbance, occurrence guarantees are not provided for the optimality of wind turbine on frequency regulation |
| [152]     | (i) Provides an appropriate way for the penetration of number of renewable energy sources to power grids | (i) Introduction rate of smart grid should be limited to maintain their operational efficiency |
| [153]     | (i) Reduces the impact of cyber attack and fault on the sensors of grid-connected DER units | (i) Sensor-based approach, if sensor fails all control and data information is to be lost |
| [154]     | (i) Adaptive fuzzy-based scheme provides better frequency regulation (i.e., fewer peaks/dips, faster settling time) as compared to dynamic equation-based scheme | (i) Modulates the gains of inertia control for a wide range speed of wind turbine stability |
| [159]     | (i) For the extraction of voltage and current component, the IPT is used for good power quality | (i) Rejection of complementary currents makes the calculation complex |
| [160]     | (i) A new pitch controller for a VSWT is proposed that adjusts tip speed ratio \(\dot{T_{so}}\) and performance coefficient \(C_{p}\) for the rated wind speed | (i) During wind speed changing, small oscillations come in low frequencies |
| [161]     | (i) Resists the power system variations on stability for making an improvement in system performance | (i) Limitation of application domain because of its feedforward network structure |
| [162]     | (i) Optimal tuning of PID controller during abrupt load changes, presence of nonlinearities | (i) Applicable only to secondary frequency control |
| [163]     | (i) Mitigates the dependency of microgrid on the online parameter (ii) Regulates the dynamic behavior of gradient droop control that performs well in load variation | (i) Applicable for a wide range of microgrids |
| [164]     | (i) For control and monitoring of power system, neural network-based schemes are presented | (i) Neural network training time is increased in tandem with the dimensions of the power system |
| [165]     | (i) Provides less overshoot, good settling time, and robustness during load disturbance | (ii) For the (BB–BC) optimization, it is necessary to limit the population to the prescribed search space boundaries and this restricts the candidate solution into search space boundaries |
| [166]     | (i) Minimizes the frequency and power deviation and also finds the global optimal solution of power optimization task | (i) Considers only the performance parameters (like settling time, maximum overshoot) without consideration of other parameters |
| [167]     | (i) Determines each distributed energy resource unit set point at microgrid secondary level control | (i) If \(K\) is increased, the eigenvalues move toward the unstable region that makes oscillation in system and leads to instability |
| [168]     | (i) Immersed infeasibility problem without fault current limiters | (i) Primary operation is independent of the availability of the communication signal |
| [169]     | (i) Methodology is particularly useful, as microgrid supplies its own load and employs its renewable sources, dispatchable units, and energy storage systems | (i) Main grid unavailability time is unknown |

IPD: Instantaneous power theory; PID: proportional integral derivative; BB–BC: Big Bang–Big Crunch; DER: distributed energy resource.

### 3.3. ESS/Energy Storage Devices

#### 3.3.1. ESS

Energy storage works as an energy backup to maintain the balance between demand and supply side. Initially, ES devices were used in nineteenth century for DC power transmission and further, it is used for lamp lighting as generators de-energize at night time [174]. Some of the ES technologies and its contribution in microgrid frequency regulation are discussed as below.

- **Battery**

The energy is stored in batteries in electrochemical form and batteries are available in different capacities from few watts to megawatts. Sodium–sulfur (NaS) batteries are good ES techniques that provide much energy density and higher power and this is an active research area [174].

- **Flywheel Energy Storage**

Flywheel ESS stores electrical energy in kinetic energy rotational form. Besides, it suffers from the drawbacks of higher standby losses, lowest energy density, and difficulty in storage expansion [174].

- **Supercapacitor**

Supercapacitor or an electric double layer capacitor is used for ES that separates two electrodes and electrolytic ions, having an energy density that is much larger than electrolytic capacitor but lower than a lead acid battery and also has a faster discharging and charging capability than batteries [174].

- **SMES**

Another form of ES is SMES in which energy is stored in the magnetic field that is created by DC flow in a superconducting coil and has a good efficiency, shorter
A PSO-based optimal sizing of a BESS is developed in Ref. [175] that enhances the system frequency during islanded mode and enables the BESS for frequency support at a reduced cost. A control system is proposed in Ref. [176] for a microgrid that has a resistive load and permanent magnet AC machine in which wind energy is used for frequency regulation and optimization technique is used in place of a control method for frequency regulation to restore it to desired values. A new active power decoupling circuit, combined with the BESS, is presented in Ref. [177] that restricts the flow of current ripples from inverter DC side to the battery but nonlinear load produces the current harmonics and still it makes the smooth operation of battery current with current ripple factor less than 5%. Software for the FESS modeling and simulation, in microgrid environment, is presented in Ref. [178] that is associated with a generator to provide resilient and secure power at utility outage. A novel method for the deployment of wind power with ESS in microgrid is presented in Ref. [179] and implemented with droop method that compels the generator for load sharing as per wind power availability. For the improvement in ripple control, a narrative technique is proposed in Ref. [180] that uses the concept of droop control based on ripple voltage injection that makes a bidirectional connection of the distributed devices for maintaining power sharing. Droop control based on battery storage system is presented in Ref. [181] for primary and secondary regulations that improve transient frequency response and recover the new steady states of frequency. During large load fluctuation, the diesel engine generator (DEG) is associated with proportional-integral (PI) controller for no error frequency regulation and it balances the active power between consumption and generation. A novel hybrid voltage/frequency droop control and active/reactive power droop control for the multi-ESS in an autonomous microgrid is proposed in Ref. [182] wherein amplitude and voltage angles are controlled by active/reactive power and ESS, controlled by real power/reactive power (PQ) droop control, actually controls reactive/active power according to voltage/frequency deviations and also controls line impedance uncertainties to make the system stable. An active power control is presented in Ref. [183] in which energy storage system (ESS)-state-of-charge(SOC) is kept in safe limits by load consumption and generated PV system power that makes the system stable. An enhanced control scheme for BESS is presented in Ref. [184] to maintain the power quality of microgrid. With the combination of virtual inertia and conventional droop control, a new frequency controller is designed that immediately mitigates the microgrid frequency oscillations. In fixed pitch-type 2 wind turbine, with the addition of power droop (P) and frequency droop (F), control is discussed in Ref. [185] which makes slope between rotor resistance and grid frequency that selects the value of rotor resistance as per grid frequency and helps in injected power reductions. A novel concept of a self-tuning virtual synchronous machine is presented in Ref. [186] that uses optimization algorithm for finding an optimal parameter to reduce cost function that is used in frequency deviations and ES power low. This strategy permits the virtual synchronous machine to control damping and inertia for frequency stability. A coordinated control method is presented in Ref. [187] that combines the ES and WTG for interim frequency support and mitigates the wind farm inertia. A new technique is presented in Ref. [188] for PV-based utility connected system in which Li-ion batteries, connected with grid through three phase inverter, fulfill the demand of grid and provide an auxiliary resource. The strategy for controlling the VSWT to implement inertial response is presented in Ref. [189] in which kinetic energy used for frequency support depending on wind speed and operational states of wind turbine (WT) and enabled the energy stored inside wind turbine to support frequency regulation. A centralized and heuristic approach is presented in Ref. [190] that shows microgrid control and management with DG sources, when connected to the single bus using master-slave strategy. During microgrid standalone mode, battery bank inverter works as a master converter that sets operating frequency and the reference voltage for remaining sources that works as a slave converter. During grid connected mode, utility grid works as a master for providing frequency and voltage to PCC. A narrative Guaranteed convergence Particle Swarm Optimization with Gaussian Mutation (GPSO-GM) algorithm is presented in Ref. [191] for the islanded microgrid mode power flow analysis problem in which for the power flow variables, steady state frequency is to be considered. A new modified power flow equation was derived for modeling the different DG’s control modes, like PQ, droop, and PV in microgrid islanded mode. PSO is used to reduce the total mismatch between active and reactive powers. Both Guaranteed convergence and mutation operators are added to PSO algorithm to find optimal solution that increases proposed algorithm speed and accuracy of results. A modified decentralized control architecture is presented in Ref. [192] for microgrid that has an inverter interface DER with conventional droop controller that controls steady-state frequency synchronization, active and reactive power sharing among inverters. Controller area network communication technique for grid synchronization is presented in Ref. [193] that synchronizes all micro sources with main grid
simultaneously and provides the robust mechanism for fault tolerant smooth operation of microgrid. The novel coordinated control algorithm is proposed in Ref. [194] in which main control center sends charging and discharging operational signals to each BESS for mitigating voltage/frequency deviations and improves the power quality of power system. ES hybridization with varying ramp rates provides minimum bus voltage variations and extends the life of ES in DC microgrid, so, a multilevel EMS for the control of hybrid ESS is proposed in Ref. [195] in which secondary control reduces steady-state deviation of bus voltage and error in power tracking, while tertiary control prevents from the high ramp rate of ES state of charge violations and bus voltage deviation. A narrative control scheme is proposed in Ref. [196] that is based on microgrid voltage and frequency output regulations theory with BESSs response. It also tracks the frequency and voltage set points while reduces the system transients during disturbance events and also control droop method key weaknesses like voltage deviations, large steady-state frequency and improves system dynamic performances. Comparative analysis of the merits and demerits of control techniques, as applied for ESSs/energy storage devices, is given in Table 3.

### 3.3.2. Contribution of EVs

Due to intermittent nature of the RESs, there is a requirement of ESS in a microgrid to maintain the power balancing during islanded mode of operation [197], that is where EVs, that behave like loads and storage also when they are connected with the grid, come to our rescue. EVs are basically both the

| Table 3. Comparison of different control techniques, as applied for energy storage systems/devices. |
|-------------------------------------------------------|---------------------------------|---------------------------------|
| Reference    | Advantages                                                                                                                                                                                                                             | Limitations                                                                                                                                                                                                 |
| [176]        | (i) Optimization technique is used in place of a control method for frequency restoration                                                                                     | (i) Overshoot comes in system frequency during wind speed variations                                                                                                                            |
| [177]        | (i) Restricts the flow of current ripples from inverter DC side to the battery                                                                                                  | (i) Both linear and nonlinear loads obtain battery current ripple factor near about 5%                                                                                                       |
| [178]        | (i) Provides resilient and secure power at utility outage                                                                                                                      | (i) Only up to a level of 0.2% of the normal frequency, it deviates the system frequency                                                                                                       |
| [179]        | (i) Compels the generator for load sharing as per wind power availability                                                                                                     | (i) System stability may be affected                                                                                                                                                              |
| [180]        | (i) Makes a bidirectional connection of the distributed devices for maintaining power-sharing                                                                               | (i) Makes the distribution system complex and requires a number of power electronics devices as active load                                                                                     |
| [181]        | (i) Improves transient frequency response (ii) Recovers the new steady states of frequency                                                                                 | (i) For big load fluctuation, the battery storage control system cannot control the frequency deviations                                      |
| [182]        | (i) Balances the active power in between the consumption and generation (ii) Controls the line impedance uncertainties (iii) Actually controls reactive/active power according to voltage/frequency deviations | (i) Load voltage continuously increases with the reduction in power because of bias-based droop control                                  |
| [183]        | (i) ESS-SOC is kept in safe limits by consumed load (ii) Generated PV system power makes the system stable                                                                  | (i) Power generation is supported for short duration with active power controller that limits ESS charging power                                                                             |
| [184]        | (i) Immediately mitigates the microgrid frequency oscillations                                                                                                                 | (i) During operation mode, the security of load supply depends upon BESS remaining capacity after disconnection from grid                                                                 |
| [185]        | (i) Makes slope in between rotor resistance and grid frequency that selects the value of rotor resistance as per grid frequency (ii) Helps in injected power reductions | (i) If wind rotor level becomes unbalanced, the proposed strategy fails                                                                                                                         |
| [186]        | (i) Reduces the cost function that is used in frequency deviations and energy storage power low (ii) Mitigates the wind farm inertia (iii) Provides an auxiliary resource                     | (i) ESS charging/discharging is not up to control level                                                                                                                                 |
| [187]        | (i) Kinetic energy used for frequency support (ii) Enables the energy stored inside wind turbine to support frequency regulation (iii) Provides a microgrid control and management with DG sources | (i) Additional spinning reserve is required for the safe operation of the system                                                                                                                   |
| [188]        | (i) Fulfills the demand of grid (ii) Provides an auxiliary resource                                                                                                          | (i) Battery size depends on the size of the feeder                                                                                                                                            |
| [189]        | (i) Controllers are not adaptable for higher order harmonic load, unbalanced and nonlinear loads                                                                            | (i) Requirement of extra power for limited time period                                                                                                                                 |
| [190]        | (i) Controls the steady-state frequency synchronization, active and reactive power sharing among inverters (ii) Utility grid works as a master in grid connected mode for providing frequency and voltage to PCC | (i) System response is not so much satisfactory regarding both power quality and transient issue                                                                                           |
| [191]        | (i) Synchronizes all micro-sources with main grid (ii) Provides the robust mechanism for fault tolerant microgrid smooth operation                                                                                     | (i) Controller is not adaptable for higher order harmonic load, unbalanced and nonlinear loads                                                                                                    |
| [192]        | (i) Overcomes the key weaknesses such as steady-state frequency & voltage deviations, and weak transient response of droop-based method | (i) Control accuracy is degraded in case of communication failures                                                                                                                                 |

PV: Photovoltaic; ESS: energy storage system; BESS: battery energy storage system; DG: distributed generation; PCC: point of common coupling.
distributed ESS and controllable load. Vehicle-to-grid (V2G) system may work as an active power support to provide the services of frequency regulation by maintaining the load–power balance in the grid. With the implementation of good EMS, EVs have become capable of dealing with intermittent nature of RESs. Lot of work has been reported in literature on EVs and their use in microgrid for ancillary services, primarily like frequency regulation with larger objectives of achieving improved reliability, efficiency, and stability in grid operation, employing different control concepts [197–221]. As per the energy consumption and driving force of EVs, there are mainly three different types of EVs: (1) battery EV – using battery as a source of energy; (2) hybrid EV – using battery and fuel as a driving force; and (3) fuel cell EV – using fuel cell for electricity production.

3.3.3. Contribution of PV Inverters
The PV system does not have any inertia characteristic from kinetic energy stored and hence no direct support for frequency regulation that way. However, the PV generator has a DC-link capacitor for ES, mounted on the DC–AC inverter side that absorbs or releases the energy. If these stored energies are controlled and consumed properly by way of suitable inverter control strategy, then PV system can also be partner in frequency regulation. Many authors have proposed new strategies around these concepts which facilitate in frequency regulation [146,222–238]. The maximum power point tracking and droop controls find their mention in most of these works.

3.3.4. ESS Charging/Discharging
Due to the intermittent nature of RESs, the power supply availability is variable and in such situations, ESSs provide flexible support to the microgrid [239] in compensating for the shortfall and extracting the power in case of excess generation. So, ESSs work as emergency power buffer for the users. The rate of charging/discharging of the ESSs plays a crucial role in responding to the intermittent disturbance of the RESs. Lot of work has been reported on the use of ESS in mitigation of negative impact of the intermittency of RESs in a microgrid [174,197,239–259].

3.3.5. EV Charging/Discharging
Charging of EVs acts as a new load to the power system and hence becomes the key parameter that affects the system frequency to some extent. Many researchers have carried out focused work around the issues related to charging of EVs [133,260–262] whereas some of them focused on discharging aspects. So, V2G and G2V infrastructure and the control algorithms thereof [260–292] play a very crucial role in dealing with the intermittent nature of RESs by adjusting the EVs charging and discharging rate as per frequency deviation that measures the power imbalance [127,215].

3.4. Optimization Techniques/Approaches/Methods
DGU location and its operations affect the performance of the microgrid. Optimization methods, analytical methods, meta-heuristic methods, and computational techniques are used to solve problems like optimal DG kinds, DG capacities, DG operations, and location of DG in a microgrid. A narrative optimization method in which location and operation of DG sources are controlled by optimizing droop control parameters that enhance voltage stability and improve the voltage profiles and provide a sharing of reactive/active power in microgrid among DGU was proposed [293]. To measure/control SSS in VSC-based microgrid, a multistage fuel consumption minimization method is presented in Ref. [294] to reduce the optimization cost while considering all constraints like voltage/frequency regulation, reactive power, and stability margin that make it difficult. A virtual and adaptive virtual impedance loop based on real-time voltage and frequency control is proposed in Ref. [295] that rapidly suppresses fluctuations without consideration of communication bus and delay time. Biogeography-based optimization algorithm is implemented in Ref. [296] that tunes Q & R matrices of Linear Quadratic Regulator (LQR) controller in which Kalman filtering is used for parameter states’ estimation and based on these states, LQR generates the control signals for frequency excursions in the microgrid. The optimal power control strategy is proposed in Ref. [297] for the case when microgrid switches to island condition. In this strategy, PSO algorithm is used to control voltage/frequency that makes this method real-time self-tunable and to investigate the steady state-response, dynamic response and also drives inverter harmonic current. A control scheme is presented in Ref. [298] for bio-diesel engine-based microgrid in which additional signals from automatic generation control (AGC) loop are chosen to reduce power mismatch after load change which modifies generator mechanical input. An optimal state-feedback method is presented in Ref. [299] that uses PSO to select Q&R values with an aqua electrolyzer, hydrogen storage, fuel cell, and DEG which performs well under cyber intrusion attack by optimizing the measured frequency signal sending rate to microgrid central controller. A new time-varying controller based on General Type II Fuzzy Logic for the load frequency control of islanding
Table 4. Comparison of different optimization techniques/approaches/methods.

| Reference | Advantages | Limitations |
|-----------|------------|-------------|
| [294] | (i) Reduces the optimization cost while considering all constraints like voltage/frequency regulation, reactive power, and stability margin | (i) Increases the objective function computation time |
| [295] | (i) Rapidly suppresses fluctuations without consideration of communication bus and delay time | (i) Applicable only for PV-based microgrid system |
| [296] | (i) Kalman filtering is used for parameter states’ estimation (ii) LQR generates the control signals for microgrid frequency excursions | (i) As wind energy conversion system (WECS) participating in frequency control, it decreases the capacity of battery |
| [297] | (i) Controls the voltage/frequency control mode (ii) Investigates the steady-state response, dynamic response and also drives inverter harmonic current (iii) Investigates the system parameter variation and load variations with higher accuracy | (i) Transients are not removed completely, it will come for shorter duration |
| [298] | (i) Performs well under cyber intrusion attack | (i) When the system is in transient time, then controller acts upon at the very first moment and creates frequency oscillations |
| [300] | (i) Used for grid topologies, renewable sources, and different loads | (i) It does not provide stability to the system for longer duration |
| [301] | (i) Ensure a capacity of maintaining generation load balance during system parameter variation and load variations with higher accuracy | (i) Provides microgrid system stability for shorter duration only |
| [302] | (i) Restores voltage/frequency of the system during load variations (ii) Optimizes ITAE, real-time, settling time objective function that provides a good response | (i) Reactive large load change has more oscillation than other disturbances |
| [303] | (i) Recovers frequency and resolves frequency oscillations caused by measurement errors even in presence of fairly large communication delay time (ii) Gives a robust performance when communication delay with large variation values is unknown | (i) Processing delays in performances will come with communication delays |
| [304] | (i) Makes the optimal allocation of power among DG sources without microgrid central controller | (i) Microgrid central controller is not cooperated in its control functions |
| [305] | (i) Minimal load curtailment and minimizes the generation cost during microgrid islanded mode | (i) Large number of constraints exist in both operational modes of microgrid that make formulation complex |
| [306] | (i) The interests of all participants are considered so that the coordination and regulation of the micro-DGs in the microgrid system can be realized | (i) Applicable only to decentralized control method |
| [307] | (i) Preserves the weighted geometric means of the voltages | (i) Creates a power flow equations set, whose solvability further investigated |

LQR: Linear Quadratic Regulator; DG: distributed generation.
solved simultaneously at different computing nodes. The linear quadratic differential game theory is adopted in Ref. [308], to control the frequency of microgrid that has a multiple DGs which also considers the coordination and regulation of multiple DGs in an islanded microgrid system. A narrative power consensus algorithm is presented in Ref. [309] for DC microgrids that has a feature of second graph which represents the communication network for the information exchange regarding instan-
taneous powers and adjusts the injected current and also creates a nonlinear consensus system that is composition of differential-algebraic equations which are further analyzed via Lyapunov functions inspired by the physics of the system. Comparative analysis of the merits and demerits of optimization techniques/approaches/methods is given in Table 4.

3.5. Shiftable/Controllable Load

3.5.1. Shiftable Loads
Managing the shiftable loads like heat pumps, water heaters, air conditioners, refrigerators and freezers, washing machines, etc. is an active research area. The user can participate in managing the loads during peak hours by possible shifts of its consumption, keeping in view the load curve optimization, for managing the peaks. The shiftable load strategies have been proposed in the recent past by many researchers to address the issue of frequency regulation [310–333] wherein interruptible load management and direct load control are the most commonly used load management approaches employing a number of control concepts. Therefore, the shiftable loads are definitely advantageous and can play an active role in addressing the negative impact of intermittency of RESs and thereby help in frequency regulation.

3.5.2. Heating, Ventilation, and Air Conditioning
Demand response techniques such as reducing peak demand, reducing reserve margins, etc. are adopted to deal with the issues and challenges arising out of the intermittency of RESs connected in a MG so as to maintain grid stability and reliability and improve energy efficiency. So, the electric load’s inherent flexibility without disturbing the customer comfort becomes a reasonable way to support ancillary services. Therefore, implementation of control strategies for the loads to provide system services becomes a key technical issue [334]. Building loads play a very important role in the electric power system as they consume major chunk of total electricity and there too half of the total energy consumptions goes to the Heating, Ventilation, and Air-Conditioning (HVAC) loads. Therefore, control over HVAC loads of the building by using suitable strategy can facilitate the ancillary services in the system. Commercial building HVAC systems have been investigated by many researchers in respect of used to providing ancillary services like frequency regulation [335–350]. For the purpose of frequency regulation, control frameworks utilizing various strategies/algorithms have been proposed for HVAC loads of residential buildings as well [351–362].

4. Conclusions

A recent perspective on the frequency control issues in microgrids has been presented in this paper. Due attention has been paid to recent developments such as the use of intelligent control with the Fuzzy logic concept and other evolutionary algorithms. Special attention has been drawn on the categorization of different frequency control schemes, as reported in the literature, for microgrids that highlight their salient features. The categories include DR schemes including the new trends in EDRPs; control strategies; ESSs including the new trends like EV charging and discharging; optimization approaches; loads; especially the controllable ones like prosumers, smart homes, and shiftable loads, heating ventilation and air conditioning systems, etc. Although the authors have sincerely attempted to present the most comprehensive review on frequency control issues, however, still some valuable papers might have been missed. Authors would like to apologize for exclusion of some such papers on frequency control issues of microgrids, if any.

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