IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received November 27, 2021, accepted December 9, 2021, date of publication December 13, 2021,
date of current version December 27, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3135083

A Review on Microgrids' Challenges & Perspectives

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ABSTRACT Due to the sheer global energy crisis, concerns about fuel exhaustion, electricity shortages, and global warming are becoming increasingly severe. Solar and wind energy, which are clean and renewable, provide solutions to these problems through distributed generators. Microgrids, as an essential interface to connect the power produced by renewable energy resources-based distributed generators to the power system, have become a research hotspot. Modern research in the field of microgrids has focused on the integration of microgrid technology at the load level. Due to the complexity of protection and control of multiple interconnected distributed generators, the traditional power grids are now outmoded. Microgrids are feasible alternatives to the conventional grid since they provide an integrating platform for micro-resources-based distributed generators, storage equipment, loads, and voltage source converters at the user end, all within a compact footprint. A microgrid can be architected to function either in grid-connected or standalone mode, depending upon the generation, integration potential to the main grid, and consumers' requirements. The amalgamation of distributed energy resources-based microgrids to the conventional power system is giving rise to a new power framework. Nevertheless, the grids' control, protection, operational stability, and reliability are major concerns. There has yet to be an effective real-time implementation and commercialization of micro-grids. This review article summarizes various concerns associated with microgrids' technical and economic aspects and challenges, power flow controllers, microgrids' role in smart grid development, main flaws, and future perspectives.

INDEX TERMS Distributed energy resources (DERs), distributed generation (DG), electrical energy storage devices (EESDs), frequency control, micro-resources, microgrids (MGs), microgrid control, power quality, power system stability, PQ droop, renewable energy resources (RERs), smart grid (SG).

I. INTRODUCTION

In recent years, the rapid modernization of countries has tremendously increased the electricity demand. Conventional energy resources like coal, diesel, gas, etc., cannot meet the power demands. Also, these resources have harmful environmental effects. Scientists are trying to switch the current conventional energy resources-based power system to renewable-energy-based systems to cater to the energy demands. So, the implementation and popularity of renewable energy resources (RERs) is increasing due to extensive utilization, and more and more technologies are being developed to utilize RERs [1]. Table 1 lists the statistics of the top ten countries producing electricity from RERs in 2019. Fig. 1 depicts the percentage of power generation by various RERs in 2016 by International Renewable Agency, Abu Dhabi [2]. Fig. 2 and 3 graphically show the current and future pace of energy output and entire generation from RERs, respectively. So, the conventional power system is becoming more and more complicated and prone to reliability and stability issues due to increased penetration of RERs-based power plants [3]. The proliferation of electric grid networks, the deterioration in the generation of primary energy resources, and the use of traditional electrical transmission and distribution networks make the system less reliable [4]. So, new solutions such as distributed generation (DG), RERs

The associate editor coordinating the review of this manuscript and approving it for publication was Zhouyang Ren.

based microgrids (MG), and energy storage systems (ESS) emerged in recent decades as feasible solutions. A statistical survey shown in Fig. 4 depicts that MGs are predicted to grow significantly in this decade, with annual capacity installation and spending expected to climb fivefold from 2018 to 2027.

A microgrid consists of DG's, Energy Storage Devices (EESDs), and local loads to provide energy to critical locations. The principal purpose of MG is to provide system stability during various network disruptions [5], [6]. Numerous definitions [7] and functional classification schemes [8] have been cited for MGs in the literature. One of the precise definitions given by the MG Exchange Group at the US Department of Energy is as follows:

"A microgrid is the system-concept of multiple but coordinated loads and generation units, and of islanding from the grid, that operates as a controllable structure to the main grid and constrained within well-defined electrical boundaries." An MG may connect/disconnect to the utility grid, enabling it to serve in both grid-tied and autonomous modes [9].

TABLE 1. Top ten countries with maximum power production from RERs in 2019 [10].

Country	Generation (GW-h)
China	82,250
United States	63,149
Brazil	54,920
Germany	50,221
UK	37,303.38
Thailand	31,980.148
Japan	27,208
India	20,026.514
Italy	19,562.583
Finland	13,291

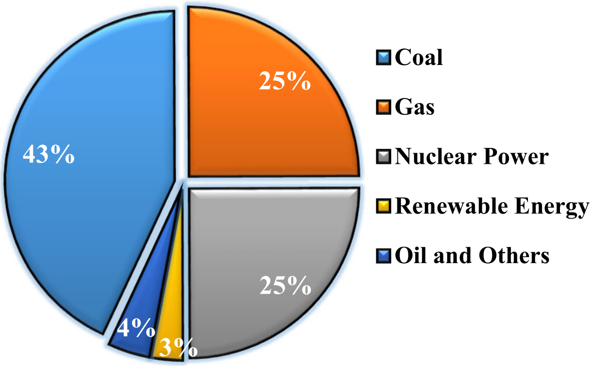

FIGURE 1. Power production from several resources 2016 [2].

Injection of an MG into the power sector has several functional edges over the conventional system like:

1. Reduced carbon emissions

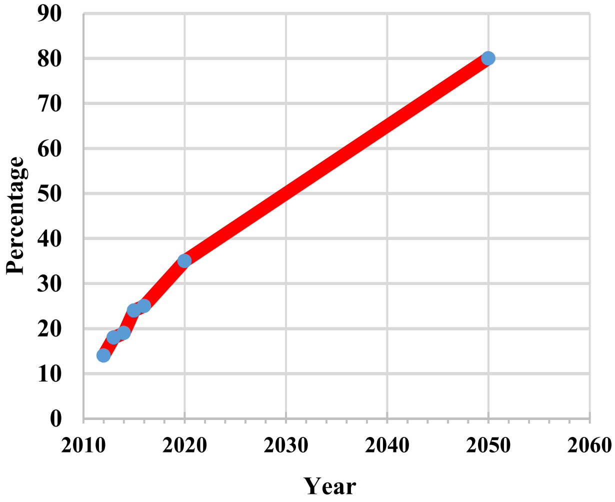

FIGURE 2. Future rate of increase of power production from RERs [2].

2. Continuous and independent supply of power to all micro-resources and loads in isolated mode
3. Helps sustainable operation of the local grid, thus improving overall power system's quality
4. Plug-and-play capabilities for switching between grid-connected and isolated modes
5. Operates as a backup power source in the case of a power outage on the main grid.

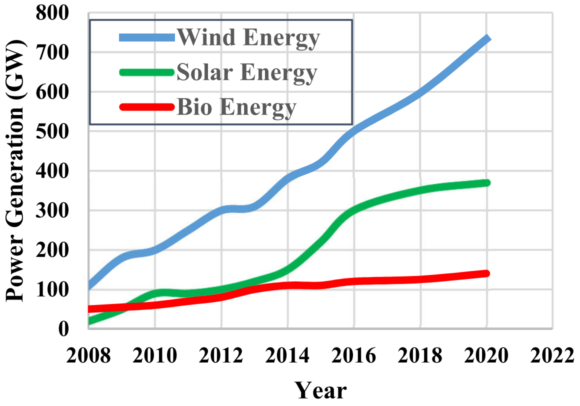

FIGURE 3. Total power production from renewables [2].

Conventional distribution networks imply unidirectional power flow from the substation to load [12]. The incorporation of an MG in the distribution network, on the other hand, transforms the prototype of unidirectional power flow into a bidirectional one. If not engineered carefully, MG integration to the conventional system could also face negative implications, such as protection, control, quality, supply dependability, outage resynchronization time, and safety. [13]. Further research and careful technical designs could successfully avoid the adverse effects of MG integration on electric supply systems. In addition to these challenges, there are still several concerns about MG operation that must be addressed for an overall optimal system.

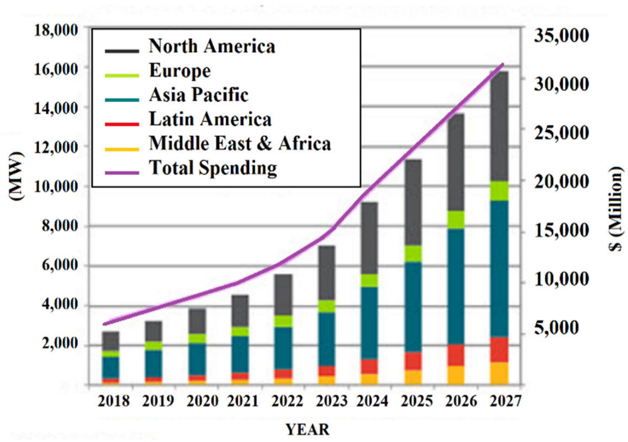

FIGURE 4. Annual microgrid capacity and spending, base scenario 2018–2027 [11].

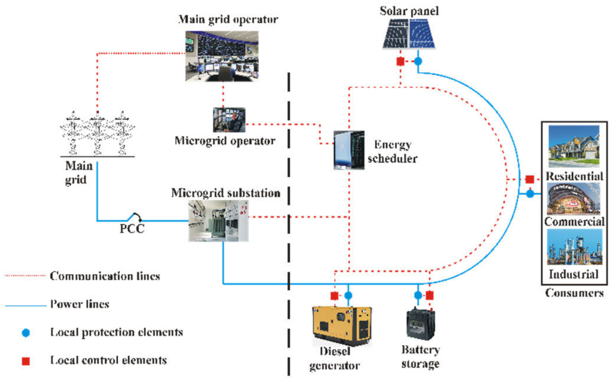

FIGURE 5. Design architecture of an MG [15].

Solar photovoltaic, fuel cells, gas engines, windmills, and internal combustion engines (ICE) are just a few of the prime mover technologies that make up an MG [14]. However, to enable flexible operation, photovoltaic systems, fuel cell technologies, energy storage systems, and wind technologies necessitate voltage source inverters and adequate controllers. The purpose of this article is to review the technical and economic aspects of MG, summarize the recent control strategies, give an overview of technical challenges and their possible solutions, MG's limitations, and future prospects. This review paper is organized as: Section 2 discusses technical aspects of MGs. Section 3 summarizes economic and market considerations. Section 4 reviews various controllers for power flow. Section 5 highlights the technical challenges and their possible solutions. Section 6 addresses the significance of MG in the realization of smart grid deployment. In Section 7 and 8, the limitations and prospects of MGs are examined, respectively. Finally, Section 8 concludes this survey.

II. TECHNICAL ASPECTS OF MGs

This section reviews technical aspects related to MG integration to the power system. Fig. 5 shows an MG's design and associated components, such as distributed generators, storage system, and local loads.

A. HARMONICS

Optimization of MGs' standalone and grid-connected operation is essential to achieve a high degree of reliability [16]. Harmonics pose a threat to the electrical network's ability to operate reliably and consistently if no precautions are taken into account [17]. The heat dissipated by the charging-discharging of capacitors deteriorates the harmonics in case of a DC MGs' DC-link. As a result, the safety of electrical energy storage systems is jeopardized since they are more responsive to harmonics [18]. Power electronic devices are the major cause of harmonic appearance in the power system network. In literature, several harmonic reduction techniques are classified as active or passive power filtering. Active filters are used to remove harmonics of any order, while passive filters are employed to attenuate higher-order harmonics. [19]. Halim *et al.* proposed a selective harmonic elimination method for a single-phase cascaded H-bridge (CHB) multilevel inverter. The proposed method efficiently eliminates the lowest-order harmonics and gives a better harmonic profile of output voltage [20]. The frequency adaptive multistage harmonic oscillator (MSHO) control is an efficient strategy for selective elimination of the harmonics demanded by the non-linear load connected at the distribution side [21].

B. POWER IMBALANCE AND VOLTAGE FLUCTUATIONS

While functioning as a load or source, switching an MG system from grid-tied to standalone mode causes power imbalance and voltage fluctuations in the system. This could also happen due to slow dynamic response and low inertia of the micro-resources. Storage and FACTS devices are viable solutions to the aforementioned problem. Elmetwaly *et al.* proposed an adaptive-switched filter compensator (ASFC) with a developed PID-controller and a D-STATCOM with optimal tuned PID controller by using the grasshopper's optimization algorithm (GOA) to improve the overall dynamic performance of the MGs [22]. Paredes *et al.* have reviewed the resilient operational behavior of MGs and its close relation to flexible AC transmission systems (FACTS) technology [23]. Paredes *et al.* also proposed a D-STATCOM device with smart FACTS technology to improve the operational resilience of the MG. The simulation results show that the proposed technique efficiently responds to the reactive power supply to the system [24]. The voltage level with regard to the synchronizing devices must be equivalent for the standalone MG to revert to grid-connected mode. Static switches with high acceleration and precise sensing capacity are required for disconnection [25]. Hong and Cabatac presented a fault detection, classification, and localization method based on an artificial neural network. The proposed method is more efficient in classifying and locating the faults than the traditional neural network. [26].

C. POWER QUALITY

Power quality is the measurement, analysis, and enhancement of bus voltage to maintain a sinusoidal waveform at a nominal voltage and frequency [27]. It is a key component that must be handled in a grid-connected MG. Power quality issues in distributed power systems arise due to increased penetration of power electronic-based switches and non-linear loads. The presence of intermittent DGs (solar and wind) also affects the power quality of a microgrid. So, a significant decision must be made to implement advanced control techniques to mitigate the adverse effects of DG-connected MG. In the future power quality-sensitive market, poor power quality will result in poor on-grid electricity prices. Generation decentralization and keeping the adequate demand to supply ratio can improve power quality [28].

D. STABILITY

The challenges to power system stability arising due to MGs and DGs' diversified operational characteristics are highlighted in this section. Three main reasons behind the stability issues are [29]:

1. Decreased system inertia, resulting in angular instability and frequency instability.
2. Lower voltage stability as a result of reduced energy distribution; and
3. Lower frequencies' oscillations as a result of a shift in the power-sharing ratio.

Decentralizing the supply and maintaining a proper demand-to-supply ratio can improve power quality and stability [28].

E. CHANGES IN TOPOLOGY

MGs can be installed in a variety of locations, including factories, high-rise apartments, communities, houses, and countryside farmland. Various forms of MGs can be designed depending on the users' needs, the robustness of the network, and the DERs available [30]. The continuous connection and disconnection of micro-resources, loads, and EESD is the primary cause of topological changes in low voltage networks. Another cause is the intermittent RERs such as solar and wind [31], [32].

F. ELECTRICAL ENERGY STORAGE DEVICES

Although DERs like renewable energy and diesel power can meet the rising electricity demand, managing energy storage and uninterrupted distribution is problematic. Diesel engine-based DERs are intermittent and not eco-friendly. Fluctuations caused by unstable micro-sources (wind, solar) and non-linear loads significantly impact the MG's normal operation. By isolating the generation source from the load, ESS provides improved stability to MGs. Storage devices provide power during catastrophic circumstances like rain and storm and reduce the time to begin recovery actions. They help reduce oscillations, increasing the system's power factor, voltage regulation, synchronizing the erratic behavior of RERs, and achieving generation-demand balance. Emerging energy storage technologies include sodium-nickel-based batteries, superconductive magnetic storage, molten salt, ice storage [33], and Hydrogen storage [34]. A most recent development for large-scale energy storage for solar/wind-energy-based MGs is Vanadium Redbox Flow (VRF) battery. Though the capital cost of VDF batteries is high, they are a hot spot of research due to their scalability, fast response time, high storage capacity, and efficiency [35].

G. CONTROL OF STORAGE DEVICES

MGs rely on energy storage devices to effectively balance the power between RERs and loads. Precise charge-discharge control schemes are required to meet this target. Various control strategies are available in the literature. Mu-ti *et al.* described the strategy to increase the wind farm's output power rate using fuzzy control for an ESS [36]. Tan *et al.* gave a comprehensive review of the advancements of storage systems for MG applications, topologies, power electronics interfaces, control schemes, and emerging issues [37]. Other strategies include the Monte Carlo simulation method [38], neural networks (NN) [39], hysteresis current controller, Proportional-Integral and Proportional-Integral-Derivative control, sliding mode controller (SMC), and H-infinity controller [40].

H. ENVIRONMENTAL CONCERNS

The hazardous CO_2 emissions and pollutants, which produce the greenhouse effect, global climate change, and environmental threats, are major disadvantages of conventional power plants [41], [42]. Conversely, RER-based micro-resources are environmentally friendly [2]. Subsequently, it is critical to switch from fossil fuels like oil and coal to renewable energy resources. Here, the Micro-Hydro generation and monthly consumptions are 7.440 MWh and 233.7946 MWh, respectively. A power source emits 381 g of CO_2 per kilowatt-hour. The intensities are calculated based on the life-cycle analysis, including emissions from manufacturing, work, smashing, and disposal. Table 2 shows mitigation in CO_2 emissions due to RER-based MGs. Fig. 6 shows a monthly graph of CO_2 emissions from the MGs, micro-hydro, and wind farms. The data shows that when each source is used to give electricity to the load, the CO_2 emissions lower down significantly. Installing these RER- based MGs in remote rural regions indicates a positive environmental impact.

TABLE 2. Mitigation in CO_2 emissions due to RER-based MGs [43].

CO_2 Emissions (Tons/month)	Micro-hydro Generation	Wind Turbines	Solar Photovoltaic
Main Network	-	9.2	-
Restricted from Energy Resource	2.83	11.75	4.91
Mitigation due to DERs	30.8%	19%	53.4%
Using Microgrids	-	1.2	-

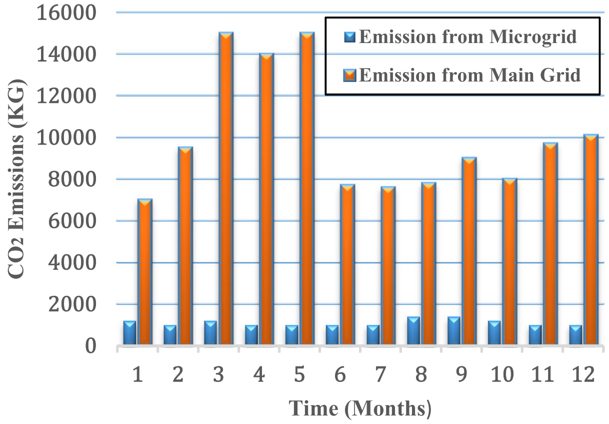

FIGURE 6. Comparison of CO_2 emissions from MGs and conventional power plants per month [2].

III. ECONOMIC AND MARKET CONSIDERATIONS

The DERs' active power, voltage, and current at the interface bus of a Voltage Source Inverter (VSI) and Current Source Inverter (CSI), respectively, govern the economics of an MG [44]. It is mandatory to control these variables to achieve optimal operation and power distribution, maximum utilization of RERs, and cost-effective operation of the entire MG. The effective regulation of MGs' output in the grid-tied mode controls the current and voltage losses caused by transformers and feeders. Furthermore, the power policies must incorporate the proper utilization of EESDs, since they impact the economics of MGs across their whole life span [45]. MGs must surmount economic, commercial, and regulatory constraints to be integrated into the utility grid. Economic hurdles include investment reduction, cost analysis, and the design of appropriate financing mechanisms [46], [47].

The participation of MGs in the market to offer their services is one of the market problems. Backing for some business models may be beneficial in the short term. However, in the long run, technical advancements, regulation, and finance policies should be such that to make them more competitive. Hence, allowing for the development of more sophisticated models of MG [48]. MG-setup, optimization techniques, and the standard model are considered significant parameters that control the optimal cost of MG [49], [50]. Development Cost and Distribution Network Operator (DNO) Costs estimate the total cost of an MG. Control and protection schemes, types of EESDs, and installation and operational cost of the equipment contribute to development cost. Voltage balance, frequency regulation, equipment maintenance, over/ under-loading, and adaptive fault limits sum together to make the DNO cost [51].

IV. POWER FLOW CONTROLLERS

The unified power flow controller (UPFC) realizes real-time control over power flow in transmission lines by adjusting the line parameters, like node voltages, phase angle, and line impedance, covering all adjustable parameters of other FACTS [52]. The MG control system plays a critical role in accommodating its reliable operation in both operating modes. The MG control system can adopt either a centralized or distributed control structure. The distributed control structure has more advantages than the centralized one regarding reliability and resilience [53].

The voltage droop control strategies are commonly adopted to control the power-sharing between parallel energy storage units in islanded DC microgrid for its low cost on the control and communication system. However, a large number of voltage and current sensors are needed in the traditional droop control method [54]. The Droop approach for power-sharing control means controlling techniques that function without inter-unit communications to direct the production of individual DGs matching a specific load [55]. However, the widespread implementation of the droop schemes over coordinated power-sharing based on communication technology is due to complexity, exorbitant prices, and the supervisory system's limited reliability. The control mechanism used for inverters located in remote places is essentially drooping control. The droop technique has no inter-unit communication and coordination during load sharing, which improves system reliability, stability, and layoff during service [56]. Furthermore, the plug-and-play features allow a single module to be replaced or disconnected without shutting down the entire system. Table 3 summarizes several control approaches and their benefits and drawbacks. Moreover, Table 4 summarizes recent studies on MGs' different aspects.

A. PQ DROOP APPROACH

The shaft torque and field excitation variation regulate real and reactive power in a synchronous generator. In addition, the generators are connected and synchronized with the grid's frequency and voltage. The mechanical input power to the shaft controls the output power regulation, which varies the torque angle without altering rotor velocity or generation frequency. The approach is applied when a specific generator directly provides power to a load in an islanding situation. However, the decoupling characteristic does not exist in this islanded operation, causing the frequency to vary significantly. Similarly, the generator bus voltages can be used to control the reactive power delivered to the load. But, due to a large X/R ratio, the regulation collapses in the distribution stage. In a high reactance distribution feeder, the drawn power at the bus with PQ Droop inverter control based is presented as [57]–[59]:

$$P_i = \frac{VE_i}{X_l} sin\varphi \tag{1}$$

$$Q_i = \frac{VE_i cos\varphi - V^2}{X_l} \tag{2}$$

where,

$$X_l = Reactance\ of\ output\ power$$
$$E_i = Inverter's \text{ peak magnitude}$$
$$V = \text{bus voltage}$$

And, φ is the phase difference between bus and inverter voltage.

The inverter frequency (f_i) is regulated following the average actual inverter power. The inverter's average reactive power Q_i is also modified by varying the amplitude of the inverter voltage (E_i). This relationship may be written as [58], [60], [61]:

$$f_i = f_r - m_p(P_i - P_r) \tag{3}$$

$$E_i = E_r - n_q (Q_i - Q_r) \tag{4}$$

where, m_p and n_q are real and reactive drooping slopes and subscripts 'r' and 'i' represent the rated values and index of the inverter, respectively.

Furthermore, the optimal values of m_p and n_q decide the improved system stability and efficient load sharing. Droop slope values are typically selected so that inverters share apparent power according to their ratings. The slope constant values in this study are determined using the following formula.

$$m_p = \frac{f_{imax} - f_{imin}}{P_{imax} - P_{imin}} \tag{5}$$

$$n_q = \frac{E_{imax} - E_{imin}}{P_{imax} - P_{imin}} \tag{6}$$

Fig. 7 visually depicts the characteristics of PQ droop represented by (5) and (6). The output voltage of the inverter is drooped with reference to the reactive power, and the inverter frequency is drooped w.r.t. the active power. Resultantly, frequency is an active power control variable, whereas inverter output voltage is the reactive power control variable.

Fig. 8 depicts a control strategy for a single inverter in a drooping topology with real and reactive power. Local samples from that specific inverter are inputs to control the inverter using this control scheme exclusively. The relevant active and reactive powers are compared to reference values to produce a respective error signal. The inverter rating determines the real and reactive power reference values. Then these two error signals are compared to the inverter's nominal frequency and voltage, and then the inverter's operating voltage and frequency are determined for optimal load sharing based on the inverter's rating.

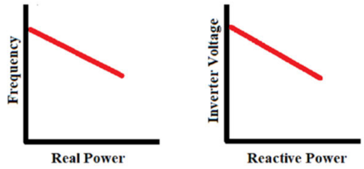

FIGURE 7. PQ droop characteristics [14], [28], [58], [59], [62].

B. VID CONTROL STRATEGY

For strong PQ coupling, virtual impedance drooping (VID) is implemented [62]–[64]. It implies that the feeder resistance has a nominal value, neither high nor low. This feeder is used in medium voltage AC systems with approximately equal line resistance and reactance, giving a unity X/R ratio. In these instances, frequency and voltage regulation cannot control real and reactive power separately, and the VID scheme is used to achieve proper load sharing. The inverter frequency (f_i) is controlled using the PQ-droop scheme as described above. VID's control method is depicted in Fig. 9. The voltage regulation formula is as follows [57]:

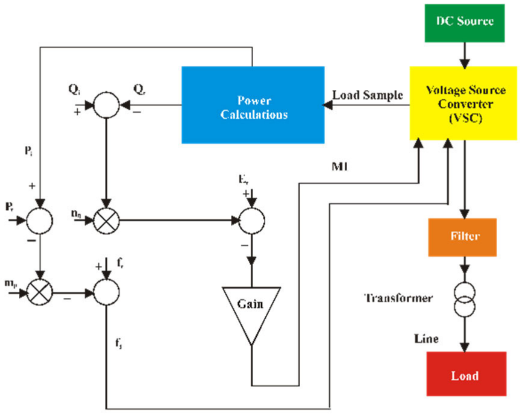

FIGURE 8. PQ droop control scheme.

$$V_{ref} = V^* - Z_{VD}(s)\,.\,i_0 \tag{7}$$

Or

$$V_{ref} = V^* - L_D \frac{s}{s+\omega_c} . i_0 \tag{8}$$

where,

V^* *is the output Voltage at no load*

$Z_{VD}(s)$ *is virtual impedance*

ω_c, *highpass filter's cutoff frequency*

C. V-P DROOP AND F-Q BOOST SCHEME

The standard PQ droop scheme operates well for the high voltage MG. On the other hand, the VID scheme works effectively in a medium voltage MG having strong PQ coupling. However, traditional PQ and VID control schemes fail for a low voltage MG with a high impedance feeder. Equation (13) shows that the increase in the inverter voltage (E) increases active and reactive power. In this case, reactive power rises with the rise in power angle (φ), while active power reduces with the rise in φ. Fig. 10 shows the electrical connection based on the decoupled output impedance between a common AC bus and an inverter. The following equations express the injected real and reactive powers to bus [65], [66].

$$P = C\,cos\theta + D\,sin\theta \tag{9}$$

$$Q = C\,sin\theta + D\,cos\theta \tag{10}$$

where,

$$C = \frac{EV}{Z} cos\varphi - \frac{V^2}{Z} \text{ and } D = \frac{EV}{Z} sin\varphi$$

E, V *is Voltage amplitude and Bus Voltage, respectively,* φ, θ, Z *are the power angle, phase angle and magnitude of output.*

Assuming the impedance to be purely resistive, (9) and (10) can be recast as:

$$P = \frac{EV}{R} cos\varphi - \frac{V^2}{R} \tag{11}$$

$$Q = -\frac{EV}{R} sin\varphi \tag{12}$$

The complex power can be expressed by combining (11) and (12), as:

$$S = \frac{1}{R}(-V^2 + EV.e^{-j\varphi}) \tag{13}$$

In actual cases, ϕ is so small enough that the Equations (11) and (12) become:

$$P = \frac{V}{R}(E - V) \tag{14}$$

$$Q = -\frac{EV}{R}\varphi \tag{15}$$

Resultantly, P and Q can be controlled by adjusting the amplitude of the output voltage (E) of the inverter. The control signal can be expressed as [58]:

$$f_i = f_r - m_q(Q_i - Q_r) \tag{16}$$

$$E_i = E_r - n_p(P_i - P_r) \tag{17}$$

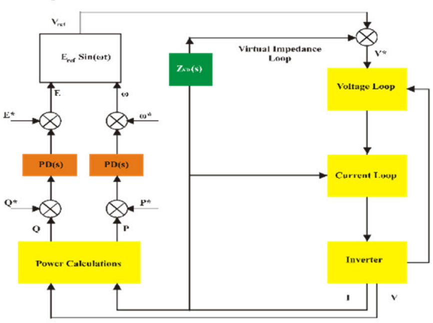

FIGURE 9. VID control scheme [67].

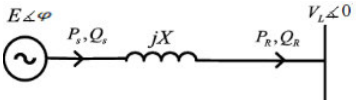

FIGURE 10. Equivalent circuit of a DG unit connected to the common AC bus [62], [65], [68].

Fig. 11 graphically elaborates the characteristics of voltage-real power and frequency-reactive power boost. Fig. 12 shows a block diagram of the control scheme. Here, the inverter's output voltage (E) is drooped against real power, and the inverter's frequency (f) is boosted w.r.t. reactive power. This control method makes it easier to control a low voltage AC MG with high resistance transmission lines [65]. Only local samples for the particular inverter are needed as inputs to perform this control system. The error signals are generated by calculating P and Q from the input samples and comparing them to the reference P and Q, respectively.

The P and Q reference values are the critical parameters that are dependent on the inverter rating. Based on the load demand and the inverter's rating, the operating voltage and frequency of the particular inverter may be calculated by analyzing these error signals to the inverter's nominal frequency and voltage.

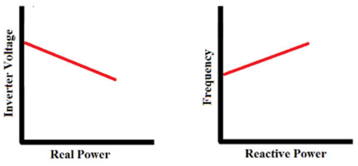

FIGURE 11. Characteristics of V-P droop and F-Q boost.

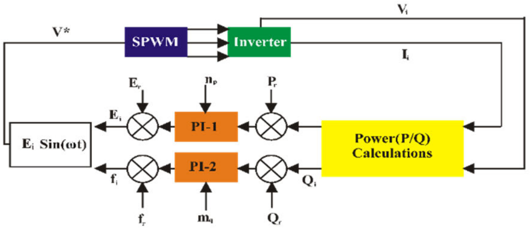

FIGURE 12. V-P droop and F-Q boost control scheme [69].

V. TECHNICAL CHALLENGES AND POSSIBLE SOLUTIONS

A. CHALLENGES

1) OPERATION

Since MGs can switch from grid-tied to the islanded mode of operation, large discrepancies between generation and demands emerge, causing significant frequency and voltage control issues [133]. The "plug and play" functionality can cause substantial problems if the connect-disconnect operations simultaneously include many generators [134].

2) COMPATIBILITY

An MG could include a range of components, like diesel engines, wind turbines, energy storage, combined heat and power, inverters, electrochemical capacitors, information and communication devices, software applications, etc. Each component's generation potential, startup time, shutdown time, inertia, operational cost, charging/discharging rate, control, and communication limits are different. These differences in the parameters give rise to compatibility issues [135].

3) INTEGRATION OF RERS

RERs' uncertainty, unreliability, and climate dependency are significant impediments to their integration into the power

TABLE 3. Several control strategies' benefits and limitations.

Reference	Control Strategy	Benefits	Limitations
L. Jia *et al.* [54]	Sliding Mode Control	Strong power-sharing. Fast dynamic response. Small steady-state error. Ability to maintain DC link.	The amount of load charge, filter capacity, and the capacity of DG units should be considered in the design domain of the controller.
M. C. Chandorkar *et al.* [70] F. Katiraei and M. R. Iravani [71]	PQ Droop	Simple implementation. Greater flexibility and expandability.	Inadequate V-F regulation. Poor dynamic response and harmonics. Effect of physical parameters on performance.
J. M. Guerrero *et al.* [57], [65] Y. Li and Y. W. Li [72] X. Yu *et al.* [73]	V-P Droop and F-Q Boost Scheme	Simple implementation. Applicable to high-resistance TL.	Poor V-F regulation. Dependence on physical variables.
K. De Brabandere *et al.* [58] A. Moawwad *et al.* [74] J. C. Vasquez *et al.* [75] H. Hanaoka *et al.* [76] G. Yajuan *et al.* [77] Y. A. R. I. Mohamed and E. F. El-Saadany [78]	Complex Line Impedance Droop Control	Better voltage regulation.	A pre-knowledge of line impedance is required.
R. Majumder *et al.* [79], [80]	Angle Droop	Better frequency regulation.	Requires smart information communication based on GPS. Inadequate power-sharing.
R. Majumder *et al.* [81], T. L. Vandoorn *et al.* [82], [83]	Constant Power Band Based Droop	Within the permissible voltage limits. In line with the parameters of a micro-resource. MPPT based efficient Energy usage.	Affects the overall efficiency due to the requirement of a separate controller at each stage.
J. M. Guerrero *et al.* [57], [63] W. Yao *et al.* [62] T. L. Vandoorn *et al.* [84]	VID Control	Independent of physical parameters. Better system stability.	Voltage regulation is not assured.
J. M. Guerrero *et al.* [85]	Optimized Virtual Impedance	Non-linear load's power-sharing. Reduction in point of common coupling's harmonic voltage.	A pre-knowledge of physical parameters is required. Low-bandwidth communication.
C. T. Lee *et al.* [86] J. He *et al.* [87] K. De Brabandere *et al.* [58] Y. Li and Y. W. Li [72], [88]	VFT Method	Decoupled PQ Control.	No guarantee that all DGs have the same transformation angle. A pre-knowledge of physical parameters is required.
Y. Li and Y. W. Li [89]	Adaptive Voltage Droop Control	Better stability and power-sharing.	A pre-knowledge of physical parameters is required.
E. Rokrok and M. E. Golshan [90] J. He and Y. W. Li [91]	Synchronized Reactive Power Compensation	Better power-sharing. Independent of physical parameters.	Low bandwidth communication is needed.
J. He and Y. W. Li [92]	Coordinated operations based on Droop Control	No communication delay. Independent of physical parameters. Better power-sharing.	Low bandwidth communication is needed.
B. Jiang and Y. Fei [93] C. T. Lee *et al.* [94] C. X. Zhang and Y. Zeng [95]	Q-V Dot Control	As simple as conventional droop control.	Prone to de-stabilization. The steady-state solution is critical to calculate. Depends upon the initial conditions.
C. T. Lee *et al.* [96] C. K. Sao and P. W. Lehn [97], [98] Q. C. Zhong [99] A. Tuladhar *et al.* [100] D. J. Perreault *et al.* [101]	Single Variable Control	Independent of physical parameters. Perfect for both linear and non-linear loads.	Voltage harmonics. Challenges in voltage measurements.
M. Fusero [102]	Virtual Generator Mode (VGM) Primary Control	Guarantees fast V/ F dynamics in an autonomous mode of operation. Gives rapid control actions during the grid-tied mode, too, enabling V-F support (GSM-FV). Provides power control by reference signals from the secondary level control (GSM-PQ).	Stability issues while transitions between the two operating modes.
S. M. Ashabani and Y. A. R. I. Mohamed [103]	Proportional Resonant	Better performance due to current controller. Zero steady-state error.	Poor harmonic profile. Complex system.
J. C. Vasquez *et al.* [75]	Hysteresis Current Control	Simple implementation. Fast-transient response	Resonance issues. Power imbalance. Harmonics and poor voltage regulation.
X. Xu *et al.* [104]	Fuzzy Logic Control	Simple implementation. Independent of parameter variation. Beneficial for non-linear systems.	Slow controlling response.
Y. Liu *et al.* [105], H. H. Huang *et al.* [106] S. Augustine *et al.* [107]	Adaptive Droop	Simple implementation. Better voltage regulation and power-sharing.	System parameters are affected.
C. X. Dou and B. Liu [108], A. Anvari-Moghaddam *et al.* [109]	Multi-Agent System (MAS)	Robust control action. Better performance under uncertain disturbances Better flexibility and efficiency.	Communication delay. Poor performance without communication links.
F. Habibi *et al.* [110]	H-Infinity Controller	Applicable to both linear and non-linear systems. Robust control action.	Complicated mathematical model Slow dynamics.

TABLE 4. A summary of recent studies on MGs' different aspects.

Discussion's Subject	Summary
Building MGs	Several merits and demerits of hierarchical control strategies for MGs' design are described in depth. The three layers structure of hierarchical control is explored, with the significance of each control layer in designing MGs [111].
Control of inverters	The survey focuses on MGs' unplanned islanding with inverter control presenting basic architecture and regulation schemes [112].
Demand-side management	The authors have tabulated the demand-side management strategies, optimization objectives, and cost optimization strategies [113].
Distributed generation systems	The hierarchical control structure for MGs, significant innovations in RERs-based DGs, and power converters parallel to the grid responsible for voltage and frequency formation are investigated [114]. DERs, energy storage methods, and emerging controllers using soft computing algorithms in islanded and grid-tied modes are summarized [115].
Energy management systems	A comprehensive review presenting several control schemes, classification, and comparative analysis of MGs' EMS has been given [116].
Frequency regulation	This research reviewed various frequency control approaches and strategies in microgrids and classified them into distinct groups based on available literature [117].
Hybrid energy storage system (ESS)	Hybrid ESS for MG applications, economic analysis, and design methodology, by investors and engineers' perspectives, are studied [118]. The recent control strategies are shown in terms of their advantages and disadvantages. The novel local RERs-based power distribution system with energy storage is investigated [119]. Technical developments in the battery-supercapacitor-based Hybrid ESS in standalone MG, control schemes, and energy management system (EMS) are analyzed [120].
Layers structure	An analysis of both research and industry documents and a comparison of several definitions provided by notable authors have been conducted to establish a strong foundation for the MGs paradigm. Layer structure facilitates the ability to analyze, search, and compare MG data. Subsequently, this work expands on previous research by including the environment concept as an essential determinant of the MG [121].
Microgrid technologies	MGs' typical design structure, protection and control strategies, and power quality are studied [122].
Model predictive control	The study examined model predictive control in independent and networked MGs, encompassing converter- and grid-level control algorithms performed on the hierarchical control structure [123].
Power electronics converters	The authors gave a literature survey for the power electronics converters to incorporate DERs with ESS to MGs [124].
Power quality improvement	The most commonly used power quality techniques and FACTS devices for system stability are studied [125].
Reactive power compensation	An MG is modeled based on real-world scientific information, and power quality issues are studied by several controllers and devices [126].

grid. Subsequently, the output power of these resources might fluctuate dramatically and often, making MG unstable [136], [137]. Also, increasing RERs' integration may generate congestion in distribution systems [138].

4) PROTECTION

The most difficult technical issue of DGs integrated into MG is system protection. For MGs working in either grid-connected or islanded mode, the protection system must be robust enough to respond to all forms of faults [139]. The protection system should be capable of quickly disconnecting the MG from the main grid during any abnormality, ensuring the DGs, lines, and loads' protection. The following factors should be considered for the protection issues [140]:

1. Integration of distributed generators with the distribution system
2. Current fault level fluctuations
3. Unexpected relay trips
4. Discoordination or reduced position of relays
5. Accidental disconnections.

Thus, the protection strategies must be up to the mark to have an improved and continuous supply. Fault current detection, isolation from the grid network, and an automated re-coordination must all be done with smart devices [141]. Since the fault currents' magnitudes depend on the MGs' operating mode, they can differ drastically between grid-connected and standalone modes of operations [142]. For radial distribution systems, traditional power systems were developed with unidirectional fault current flow. However, when DGs are integrated into the main grid through MGs, the fault currents flow bi-directionally. A rapid static switch interfaces the MG to the main grid to protect it from all types of outages in both operating modes [134]. Table 5 summarizes the most recent surveys on the protection of MGs.

5) REGULATION

MGs' regulation is an important challenge since it directs and facilitates DERs' penetration and integration into the utility grid. However, regulations for MG deployment are constrained, making proper usage of MGs problematic.

TABLE 5. A summary of recent studies on MGs' protection.

Reference	Summary
D. Gutierrez-Rojas *et al.* [127]	The review addresses the advancements in protection, a comparison of the optimization methods, and information and communication technologies (ICT) with a prospective outlook on communication technology's implementations, and the potential of 5G wireless systems and multi-connectivity to enable adaptive protection.
L. Zhang *et al.* [128] S. Mirsaeidi *et al.* [129]	Existing protection schemes and principles, fault detection techniques are presented in detail along with protection devices, and earthing options.
A. Chandra *et al.* [130]	Topological changes in DC MGs' architecture have substantial impacts on existing protection schemes. The increased fault currents are a barrier to MG protection in the short term. This paper reviews and discusses the protection issues associated with DC MGs.
L. Che *et al.* [131]	Different protection challenges associated with MGs and possible solutions for relay coordination have been discussed. It is shown that the hierarchical protection strategy based on the communication-assisted directional OC relays and the localized differential scheme would provide efficient protection schemes for the microgrid in both grid-connected and island modes.
A. Dagar *et al.* [132]	The authors have comprehensively reviewed protection strategies, current interruption approaches, protection devices, and standards for AC, DC, and Hybrid Microgrids.

Furthermore, interconnection schemes for MGs and the utility systems are developed to standardize and optimize the effects of MGs' integration, so the main grid's performance and safety are not compromised [143]. In the event of any faults or breakdown, these protocols must promptly disengage the MG from the grid. However, the most frequently voiced concern about MGs' integration into the utility grid is the high connection expenses [144].

6) SMART CONSUMER

Members of the future smart grid are smart consumers who play a significant part in balancing demand and supply. They are primarily concerned with lowering the electricity cost or at least sustaining current comfort levels, accessibility, and usage simplicity [145]. Utilizing ICT devices in residentials has become ubiquitous due to customers' active participation in demand management [146]. In the coming days, energy management systems (EMS) will be an integral part of smart homes to optimize energy utilization, reduce utility bills, and meet supply challenges while maintaining the required degree of comfort for users [147].

B. POSSIBLE SOLUTIONS

The following are some of the potential solutions for MGs' technical challenges proposed in the literature:

- FACTS devices such as the static VAR compensator (SVC), static synchronous compensator (STATCOM), unified power flow controller (UPFC), static series synchronous compensator (SSSC), alleviate stability and reliability challenges caused by the integration of RERs to MGs. Moreover, filters embedded into these devices attenuate harmonics caused by power circuits [137]. Shuai *et al.* examined the stability classifications and analysis methodologies for MG [148].
- Zamani *et al.* [149] proposed a microprocessor-based MG protection technique using overcurrent relays and directional elements for both modes of operation. Differential Protection Schemes [150], Symmetrical Component Theory [151], and Adaptive Protection [152] are some of the other techniques.
- External protection devices, e.g., fault current limiters, fast static switches, and ESS, are used to protect from fault currents [153].
- Novel algorithms have been investigated to reduce system costs. Khodayar *et al.* used a high-reliability distribution system (HRDS) to evaluate economic indices in microgrids and compared it to traditional distribution systems [154]. Wang and Wang implemented the rolling-horizon optimization method to minimize the operational costs in the normal operation mode of MG [155]. To minimize the MG's total operation cost, Khodaei proposed a novel islanding criterion (T-τ islanding criterion) [156]. Mahmoodi *et al.* presented a distributed economic-dispatch-strategy for MGs with multiple ESS to achieve the minimum cost operation equivalent to centralized dispatching [157]. Khodaei and Shahidhepour proposed a mixed integer programming optimization method to reduce the total system costs [158]. A decentralized voltage control technique with two control layers was proposed by Ahn and Peng [159].
- A proposal for the implementation of an intelligent hybrid automatic transfer switch (HATS) for islanding detection method (IDM) is given by Papadimitrious *et al.* This technique can detect and manage MG operation modes and status [160].

VI. MGs' SIGNIFICANCE IN SMART GRID REALIZATION

The advancement of power grids is referred to as smart grids [161], [162]. "An SG is a power system that can efficiently implement the behavior of all users connected to it–generating units, clients, and those who do both–to ensure economic efficiency and sustainable power" [163].

The following factors distinguish SG from traditional grids [136], [164]:

1. Integration of autonomous RERs to achieve emission-reduction.
2. Bilateral information and power exchange, advanced sensors, and distributed computing technology.

3. Optimization of resources utilization.
4. Provision of reliable energy by demands.
5. Smart enough to self-heal in the event of a network failure.
6. Customer-oriented.
7. Immune to both electrical and cyber-attacks helps to optimize the use of assets.
8. Environment-friendly.
9. Improve power delivery and use efficiency, dependability, and safety.

Aside from these benefits, smart grids confront several challenges, such as bidirectional communications, grid integration with RES, inefficient DG deployment, and insufficient existing power infrastructure and storage. Handling generation, storage, and loads as a localized group is one technique for optimal DG use [161], [165]. MG is an integral part of the SG concept. Being a part of a larger grid, it includes all of the utility grid's components. MGs are smaller and can operate independently from the larger utility grid, whereas SGs serve at a higher utility level, such as the national grid system.

VII. LIMITATIONS OF MICROGRIDS

This section summarizes some of the MGs' significant limitations, which include the following [166],

1) The power quality, voltage, and frequency control should be such that the indices fall within specific limits.

2) The utilization of unstable DERs may fail to supply continuously, necessitating the addition of more EESDs, which require more area and regular service.

3) Resynchronization and coordination of MG to the main grid after fault removal is a big challenge.

4) The implementation of a robust protection system is one of the primary technical challenges.

5) MGs may be hampered by net metering and idle costs.

6) Suitable connecting standards must be established.

VIII. MGs' FUTURE TRENDS AND COMMERCIALIZATION

This section reviews the future trends that will be expectedly carried out for MGs' advancements [167]:

1) For both grid-tied and autonomous modes of operation, frequency and voltage schemes should be properly designed, tested, and examined experimentally.

2) Transition period from grid-tied to autonomous mode and high penetrations of DERs need to be researched more deeply.

3) For power quality, protection, control, and management, the occurrence of black-starting needs to be focused on.

4) Provision of reliable, stable, and secure power, the transformation of modern MGs to more robust, unique, smart, and dynamic power delivery network still needs practical research.

5) Harmonics produced due to non-linear loads like power electronic devices, induction motors, and electric vehicles must be mitigated. So, further researches are needed to reduce harmonics for better performance of MGs.

6) Due to the extensive penetration of DERs to MGs, demand response and load management are critical challenges in distribution networks.

7) Artificial intelligence-based approaches need to be extended for smarter communication schemes in MGs.

8) The performance of MG management schemes can be improved for better stability and more reliable and controlled power flow.

9) The AC-MG protection strategies face network and communication channel faults. These have to be improved further to provide a more reliable solution.

Societies and parks will likely be the major contributors to MGs, as they will employ them to save operational costs while also generating revenues by selling electricity to the main grid during peak demand hours. Markets are the most effective methods of balancing demand and supply. Demand response aggregators are feasible solutions for the consumers' market since they allow for loads' customized control [168], [169]. The aggregators perform the role of bridging the information and technical gaps that electrical energy networks face. Furthermore, these aggregators can be used to integrate DER technology and as respondents in the growing power market. They aid in the development of products, thus encouraging and assisting consumers in collaborating to the electricity markets by incorporating recent developments in advance metering infrastructure (AMI) and information communication technology (ICT) [170], [171]. Local Energy Communities (LECs) and MGs are also important in developing distribution networks, contributing to energy conservation, driving the grid more flexible, and providing benefits to consumers and utility.

IX. CONCLUSION

MGs serve as critical interfaces between RERs-based DGs and utility grids/loads. As the primary phase of modern grid systems, they have the potential to become a prominent building block for future SGs. They have many advantages over traditional energy systems, including improved control, flexibility, increased reliability, higher power quality, economic viability, environmental friendliness, and adaptability. Depending on the architecture, energy potential, economics, integration constraints, and utility or consumer requirements, MGs can be designed to operate autonomously or in grid-integrated modes. When in autonomous mode, an MG may experience control and protection issues due to the intermittent behavior of RER and non-linear loads. When operating in grid-tied mode, MGs encounter integration issues, which lead to control and protection issues. Grid integration and power-sharing mechanisms are critical to an MG's effective operation due to system protection, control, and stability. This review attempts to summarize various technical aspects of MGs, as well as economic and market considerations for commercialization. This article also discusses recent MG control schemes, technical issues related to MG integration to utility grids, and feasible solutions. Researchers have recently become more concerned about the use of droop control strategies. It is worth noting that there is not a strong consensus on MGs' switching and control schemes. This article also discusses the importance of MGs in implementing future Smart Grids and their limits and potentials. MGs are gaining traction as a superior alternative to meet the growing demand for reliable, environmentally friendly, and cost-effective power. MGs will contribute significantly to remote and rural electrification in the near future.

REFERENCES

[1] G. K. Suman, J. M. Guerrero, and O. P. Roy, ''Robust frequency control in interconnected microgrids: An H_2/H_∞ control approach,'' *IEEE Syst. J.*, early access, Sep. 17, 2021, doi: 10.1109/JSYST.2021.3108685.

[2] *Renewable Capacity Statistics 2017*, Int. Renew. Energy Agency, Abu Dhabi, United Arab Emirates, 2017. [Online]. Available: http://irena.org

[3] Z. Fan, B. Fan, J. Peng, and W. Liu, ''Operation loss minimization targeted distributed optimal control of DC microgrids,'' *IEEE Syst. J.*, vol. 15, no. 4, pp. 5186–5196, Dec. 2021, doi: 10.1109/JSYST.2020.3035059.

[4] Y. Yoldaş, A. Önen, S. M. Muyeen, A. V. Vasilakos, and İ. Alan, ''Enhancing smart grid with microgrids: Challenges and opportunities,'' *Renew. Sustain. Energy Rev.*, vol. 72, pp. 205–214, May 2017.

[5] O. Palizban and K. Kauhaniemi, ''Microgrid control principles in island mode operation,'' in *Proc. IEEE Grenoble Conf.*, Grenoble, France, Jun. 2013, pp. 1–6.

[6] W. Al-Saedi, S. W. Lachowicz, D. Habibi, and O. Bass, ''Power flow control in grid-connected microgrid operation using particle swarm optimization under variable load conditions,'' *Int. J. Electr. Power Energy Syst.*, vol. 49, pp. 76–85, Jul. 2013.

[7] D. E. Olivares, A. M. Sani, A. H. Etemadi, C. A. Canizares, R. Iravani, M. Kazerani, A. H. Hajimiragha, O. Gomis-Bellmunt, M. Saeedifard, R. Palma-Behnke, G. A. Jimenez-Estevez, and N. D. Hatziargyriou, ''Trends in microgrid control,'' *IEEE Trans. Smart Grid*, vol. 5, no. 4, pp. 1905–1919, Jul. 2014.

[8] F. Martin-Martínez, A. Sánchez-Miralles, and M. Rivier, ''A literature review of microgrids: A functional layer based classification,'' *Renew. Sustain. Energy Rev.*, vol. 62, pp. 1133–1153, Sep. 2016.

[9] D. T. Ton and M. A. Smith, ''The U.S. department of energy's microgrid initiative,'' *Electr. J.*, vol. 25, no. 8, pp. 84–94, Oct. 2012.

[10] *Renewable Electricity Generation Country Ranking 2019*, Int. Renew. Energy Agency, Abu Dhabi, United Arab Emirates, 2019. [Online]. Available: http://irena.org

[11] E. Wood. (Aug. 2018). What's driving microgrids toward a $3.9B market? Microgrid Knowledge. [Online]. Available: https://microgridknowledge.com/microgrid-market-navigant/

[12] J. Cardell and R. Tabors, ''Operation and control in a competitive market: Distributed generation in a restructured industry,'' *Energy J.*, vol. 18, no. 1, pp. 111–136, Sep. 1997.

[13] K. V. Vidyanandan and B. Kamath, ''Grid integration of renewables: Challenges and solutions,'' presented at the Emerg. Energy Scenario India, Issues, Challenges, Way Forward, Neyveli, India, 2018.

[14] F. D. Kanellos, A. I. Tsouchnikas, and N. D. Hatziargyriou, ''Microgrid simulation during grid-connected and islanded modes of operation,'' presented at the Int. Conf. Power Syst. Transients (IPST), Montreal, QC, Canada, Jun. 2005.

[15] S. Paul, A. Tamrakar, and N. P. Padhy, ''Demand side management based optimal scheduling portfolio of a microgrid in linear programming platform,'' in *Proc. 20th Nat. Power Syst. Conf. (NPSC)*, Tiruchirappalli, India, Dec. 2018, pp. 1–6.

[16] A. Micallef, M. Apap, C. Spiteri-Staines, and J. M. Guerrero, ''Mitigation of harmonics in grid-connected and islanded microgrids via virtual admittances and impedances,'' *IEEE Trans. Smart Grid*, vol. 8, no. 2, pp. 651–661, Mar. 2017.

[17] M. H. Karimi, S. A. Taher, Z. D. Arani, and J. M. Guerrero, ''Imbalance power sharing improvement in autonomous microgrids consisting of grid-feeding and grid-supporting inverters,'' in *Proc. 7th Iran Wind Energy Conf. (IWEC)*, Shahrood, Iran, May 2021, pp. 1–6.

[18] Y. W. Li, D. M. Vilathgamuwa, and P. C. Loh, ''A grid-interfacing power quality compensator for three-phase three-wire microgrid applications,'' *IEEE Trans. Power Electron.*, vol. 21, no. 4, pp. 1021–1031, Jul. 2006.

[19] M. A. Khan, A. Haque, V. S. B. Kurukuru, H. Wang, and F. Blaabjerg, ''Stand-alone operation of distributed generation systems with improved harmonic elimination scheme,'' *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 9, no. 6, pp. 6924–6934, Dec. 2021, doi: 10.1109/JESTPE.2021.3084737.

[20] W. A. Halim, T. Noor, A. T. Azam, K. Applasamy, and A. Jidin, ''Selective harmonic elimination based on Newton–Raphson method for cascaded H-bridge multilevel inverter,'' *Int. J. Power Electron. Drive Syst.*, vol. 8, no. 3, pp. 1193–1202, Sep. 2017.

[21] F. Chishti, S. Murshid, and B. Singh, ''Frequency adaptive multistage harmonic oscillator for renewable-based microgrid under nonideal grid conditions,'' *IEEE Trans. Ind. Electron.*, vol. 68, no. 1, pp. 358–369, Jan. 2021.

[22] A. H. Elmetwaly, A. A. Eldesouky, and A. A. Sallam, ''An adaptive D-FACTS for power quality enhancement in an isolated microgrid,'' *IEEE Access*, vol. 8, pp. 57923–57942, 2020.

[23] L. A. Paredes, M. G. Molina, and B. R. Serrano, ''Resilient microgrids with FACTS technology,'' in *Proc. IEEE PES Transmiss. Distrib. Conf. Exhib. (TD LA)*, Montevideo, Uruguay, Sep. 2020, pp. 1–6.

[24] L. A. Paredes, M. G. Molina, and B. R. Serrano, ''Improvements in the voltage stability of a microgrid due to smart FACTS—An approach from resilience,'' in *Proc. IEEE ANDESCON*, Quito, Ecuador, Oct. 2020, pp. 1–6.

[25] S. Sen and V. Kumar, ''Microgrid control: A comprehensive survey,'' *Annu. Rev. Control*, vol. 45, pp. 118–151, Jan. 2018.

[26] Y.-Y. Hong and M. T. A. M. Cabatac, ''Fault detection, classification, and location by static switch in microgrids using wavelet transform and Taguchi-based artificial neural network,'' *IEEE Syst. J.*, vol. 14, no. 2, pp. 2725–2735, Jun. 2020.

[27] J. Shailendra, ''Power quality: An introduction,'' in *Modeling and Control of Power Electronics Converter System for Power Quality Improvement*. New York, NY, USA: Academic, 2018, ch 1, pp. 1–29.

[28] P. Gaur and S. Singh, ''Investigations on issues in microgrids,'' *J. Clean Energy Technol.*, vol. 5, no. 1, pp. 47–51, 2017.

[29] P. Gopakumar, M. J. B. Reddy, and D. K. Mohanta, ''Stability concerns in smart grid with emerging renewable energy technologies,'' *Electr. Power Compon. Syst.*, vol. 42, nos. 3–4, pp. 418–425, Feb. 2014.

[30] S. Parhizi, H. Lotfi, A. Khodaei, and S. Bahramirad, ''State of the art in research on microgrids: A review,'' *IEEE Access*, vol. 3, pp. 890–925, 2015.

[31] D. H. Pham, G. Hunter, L. Li, and J. Zhu, ''Microgrid topology for different applications in Vietnam,'' in *Proc. 22nd Australas. Univ. Power Eng. Conf. (AUPEC)*, Bali, Indonesia, Sep. 2012, pp. 1–6.

[32] M. Yu and Z. H. Zhao, ''Power management for DC microgrid cluster with renewable microgeneration,'' in *Renewable Energy Microgeneration Systems*. New York, NY, USA: Academic, 2021, ch. 12, pp. 265–284.

[33] Y. Guo, Z. Zhao, and L. Huang, ''SoC estimation of lithium battery based on AEKF algorithm,'' *Energy Proc.*, vol. 105, pp. 4146–4152, May 2017.

[34] B. A. Kalwar, W. Zong, I. Ahmed, and M. H. Saeed, ''Ti atom doped single vacancy silicene for hydrogen energy storage: DFT study,'' *J. Chin. Chem. Soc.*, early access, Nov. 2021, doi: 10.1002/jccs.202100369.

[35] K. Lourenssen, J. Williams, F. Ahmadpour, R. Clemmer, and S. Tasnim, ''Vanadium redox flow batteries: A comprehensive review,'' *J. Energy Storage*, vol. 25, Oct. 2019, Art. no. 100844.

[36] A. L.-N.-E. A. Mu-Ti, C. Qin, T. E.-X. Y. Bu-La-Yin, and L. Jian-Chun, ''Application of fuzzy control for the energy storage system in improving wind power prediction accuracy,'' *Amer. J. Energy Res.*, vol. 1, no. 3, pp. 54–58, Sep. 2013.

[37] X. Tan, Q. Li, and H. Wang, ''Advances and trends of energy storage technology in microgrid,'' *J. Electr. Power Energy Syst.*, vol. 44, pp. 179–191, Jan. 2013.

[38] A. Zeng, Q. Xu, M. Ding, K. Yukita, and K. Ichiyanagi, ''A classification control strategy for energy storage system in microgrid,'' *IEEJ Trans. Electr. Electron. Eng.*, vol. 10, no. 4, pp. 396–403, Mar. 2015.

[39] G. Capizzi, F. Bonanno, and G. M. Tina, ''Recurrent neural network-based modeling and simulation of lead-acid batteries charge–discharge,'' *IEEE Trans. Energy Convers.*, vol. 26, no. 2, pp. 435–443, Jun. 2011.

[40] A. Ortega and F. Milano, ''Comparison of different control strategies for energy storage devices,'' in *Proc. 19th Power Syst. Comput. Conf. (PSCC)*, Genoa, Italy, Jun. 2016, pp. 1–7.

[41] D. Cebrucean, V. Cebrucean, and I. Ionel, "CO_2 capture and storage from fossil fuel power plants," *Energy Proc.*, vol. 63, pp. 18–26, Dec. 2014.

[42] M. O'Sullivan, M. Gravatt, J. Popineau, J. O'Sullivan, W. Mannington, and J. McDowell, "Carbon dioxide emissions from geothermal power plants," *Renew. Energy*, vol. 175, pp. 990–1000, Sep. 2021.

[43] J. Khazaei and C. Schlauderaff, "Data on reducing carbon footprint in microgrids using distributed battery energy storage," *Data Brief*, vol. 27, Dec. 2019, Art. no. 104679.

[44] S. Cai, S. Wang, C. Wang, and G. Jia, "Economic perspective of smart grid," *Automat. Electr. Power Syst.*, vol. 20, pp. 13–87, 2009.

[45] H. Asano and S. Bando, "Economic evaluation of microgrids," in *Proc. IEEE Power Energy Soc. Gen. Meeting, Convers. Del. Electr. Energy 21st Century*, Pittsburgh, PA, USA, Jul. 2008, pp. 1–6.

[46] K. B. Jones, D. Nugent, S. J. S. Bartell, and J. Hart, "The urban microgrid: Smart legal and regulatory policies to support electric grid resiliency and climate mitigation," *Fordham Urban Law J.*, vol. 41, pp. 1695–1757, Mar. 2016.

[47] F. Feijoo and T. K. Das, "Emissions control via carbon policies and microgrid generation: A bilevel model and Pareto analysis," *Energy*, vol. 90, pp. 1545–1555, Oct. 2015.

[48] M. H. Bellido, L. P. Rosa, and A. O. Pereira, "Challenges and opportunities for microgrid implementation: The case of Federal University of Rio de Janeiro," *J. Clean. Prod.*, vol. 188, pp. 203–216, Jul. 2018.

[49] J. Peng, B. Fan, and W. Liu, "Voltage-based distributed optimal control for generation cost minimization and bounded bus voltage regulation in DC microgrids," *IEEE Trans. Smart Grid*, vol. 12, no. 1, pp. 106–116, Jan. 2021.

[50] Y. Jia, Z. Y. Dong, C. Sun, and G. Chen, "Distributed economic model predictive control for a wind–photovoltaic–battery microgrid power system," *IEEE Trans. Sustain. Energy*, vol. 11, no. 2, pp. 1089–1099, Apr. 2020.

[51] P. O. Kriett and M. Salani, "Optimal control of a residential microgrid," *Energy*, vol. 42, no. 1, pp. 321–330, 2012.

[52] J. Yun, G. Chen, H. Xu, Q. Li, J. Liu, and P. Li, "Principles and functions of UPFC," in *Unified Power Flow Controller Technology and Application*, 2nd ed. New York, NY, USA: Academic, 2017, ch. 2, pp. 19–41.

[53] T. Khalili and A. Bidram, "Distributed control approaches for microgrids," in *Microgrids: Advances in Operation, Control, and Protection*. Cham, Switzerland: Springer, 2021, pp. 275–288, doi: 10.1007/978-3-030-59750-4_11.

[54] L. Jia, C. Du, C. Zhang, and A. Chen, "An improved droop control method for reducing current sensors in DC microgrid," in *Proc. Chin. Autom. Congr. (CAC)*, Jinan, China, Oct. 2017, pp. 4645–4649.

[55] R. Sedaghati and M. R. Shakarami, "A new sliding mode-based power sharing control method for multiple energy sources in the microgrid under different conditions," *Int. J. Ind. Electron. Control Opt.*, vol. 2, no. 1, pp. 25–38, Jan. 2019.

[56] E. Barklund, N. Pogaku, M. Prodanovic, C. Hernandez-Aramburo, and T. C. Green, "Energy management in autonomous microgrid using stability-constrained droop control of inverters," *IEEE Trans. Power Electron.*, vol. 23, no. 5, pp. 2346–2352, Sep. 2008.

[57] J. M. Guerrero, L. Garcia de Vicuna, J. Matas, M. Castilla, and J. Miret, "Output impedance design of parallel-connected UPS inverters with wireless load-sharing control," *IEEE Trans. Ind. Electron.*, vol. 52, no. 4, pp. 1126–1135, Aug. 2005.

[58] K. De Brabandere, B. Bolsens, J. Van den Keybus, A. Woyte, J. Driesen, and R. Belmans, "A voltage and frequency droop control method for parallel inverters," *IEEE Trans. Power Electron.*, vol. 22, no. 4, pp. 1107–1115, Jul. 2007.

[59] E. A. A. Coelho, P. C. Cortizo, and P. F. D. Garcia, "Small signal stability for parallel connected inverters in stand-alone AC supply systems," in *Proc. IEEE Ind. Appl. Conf. 35th IAS Annu. Meeting World Conf. Ind. Appl. Electr. Energy*, Rome, Italy, Oct. 2000, pp. 2345–2352.

[60] J. Feng Hu, J. G. Zhu, and G. Platt, "A droop control strategy of parallel-inverter-based microgrid," in *Proc. Int. Conf. Appl. Superconductor Electromagn. Devices*, Sydney, NSW, Australia, Dec. 2011, pp. 188–191.

[61] C. Dou, Z. Zhang, D. Yue, and M. Song, "Improved droop control based on virtual impedance and virtual power source in low-voltage microgrid," *IET Gener., Transmiss. Distrib.*, vol. 11, no. 4, pp. 1046–1054, Mar. 2017.

[62] W. Yao, M. Chen, J. Matas, J. M. Guerrero, and Z.-M. Qian, "Design and analysis of the droop control method for parallel inverters considering the impact of the complex impedance on the power sharing," *IEEE Trans. Ind. Electron.*, vol. 58, no. 2, pp. 576–588, Feb. 2011.

[63] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. Vicuña, and M. Castilla, "Hierarchical control of droop-controlled AC and DC microgrids—A general approach toward standardization," *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 158–172, Jan. 2011.

[64] J. He and Y. W. Li, "Analysis, design, and implementation of virtual impedance for power electronics interfaced distributed generation," *IEEE Trans. Ind. Appl.*, vol. 47, no. 6, pp. 2525–2538, Nov./Dec. 2011.

[65] J. M. Guerrero, J. Matas, L. G. de Vicuña, M. Castilla, and J. Miret, "Decentralized control for parallel operation of distributed generation inverters using resistive output impedance," *IEEE Trans. Ind. Electron.*, vol. 54, no. 2, pp. 994–1004, Apr. 2007.

[66] A. R. Bergen and V. Vittal, "Generation voltage control," in *Power Systems Analysis*, 2nd ed. Upper Saddle River, NJ, USA: Prentice-Hall, 1986, ch. 8, pp. 273–293.

[67] W. J. Praiselin and J. B. Edward, "Integrated renewable energy sources with droop control techniques-based microgrid operation," in *Hybrid-Renewable Energy Systems in Microgrids: Integration, Developments and Control* (Woodhead Publishing Series in Energy). Woodhead Publishing, 2018, ch. 3, pp. 39–60, doi: 10.1016/C2017-0-01772-X.

[68] X. Hou, Y. Sun, W. Yuan, H. Han, C. Zhong, and J. Guerrero, "Conventional P-ω/Q-V droop control in highly resistive line of low-voltage converter-based AC microgrid," *Energies*, vol. 9, no. 11, p. 943, Nov. 2016, doi: 10.3390/en9110943.

[69] N. Aphrodis, "Energy management and control strategy of DC source and microturbine generation system by using PQ controller and droop control in islanded mode," *Int. J. Energy Power Eng.*, vol. 7, pp. 9–18, Jan. 2018.

[70] M. C. Chandorkar, D. M. Divan, and R. Adapa, "Control of parallel connected inverters in standalone AC supply systems," *IEEE Trans. Ind. Appl.*, vol. 29, no. 1, pp. 136–143, Jan. 1993.

[71] F. Katiraei and M. R. Iravani, "Power management strategies for a microgrid with multiple distributed generation units," *IEEE Trans. Power Syst.*, vol. 21, no. 4, pp. 1821–1831, Nov. 2006.

[72] Y. Li and Y. W. Li, "Virtual frequency-voltage frame control of inverter based low voltage microgrid," in *Proc. IEEE Electr. Power Energy Conf. (EPEC)*, Montreal, QC, Canada, Oct. 2009, pp. 1–6.

[73] X. Yu, A. M. Khambadkone, H. Wang, and S. T. S. Terence, "Control of parallel-connected power converters for low-voltage microgrid—Part I: A hybrid control architecture," *IEEE Trans. Power Electron.*, vol. 25, no. 12, pp. 2962–2970, Dec. 2010.

[74] A. Moawwad, V. Khadkikar, and J. L. Kirtley, "A new *P-Q-V* droop control method for an interline photovoltaic (I-PV) power system," *IEEE Trans. Power Del.*, vol. 28, no. 2, pp. 658–668, Apr. 2013.

[75] J. C. Vasquez, J. M. Guerrero, A. Luna, P. Rodríguez, and R. Teodorescu, "Adaptive droop control applied to voltage-source inverters operating in grid-connected and islanded modes," *IEEE Trans. Ind. Electron.*, vol. 56, no. 10, pp. 4088–4096, Oct. 2009.

[76] H. Hanaoka, M. Nagai, and M. Yanagisawa, "Development of a novel parallel redundant UPS," in *Proc. 25th Int. Telecommun. Energy Conf. (INTELEC)*, Yokohama, Japan, Oct. 2003, pp. 493–498.

[77] G. Yajuan, W. Weiyang, G. Xiaoqiang, and G. Herong, "An improved droop controller for grid-connected voltage source inverter in microgrid," in *Proc. 2nd Int. Symp. Power Electron. Distrib. Gener. Syst.*, Hefei, China, Jun. 2010, pp. 823–828.

[78] Y. A.-R. I. Mohamed and E. El-Saadany, "Adaptive decentralized droop controller to preserve power sharing stability of paralleled inverters in distributed generation microgrids," *IEEE Trans. Power Electron.*, vol. 23, no. 6, pp. 2806–2816, Nov. 2008.

[79] R. Majumder, A. Ghosh, G. Ledwich, and F. Zare, "Angle droop versus frequency droop in a voltage source converter based autonomous microgrid," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Calgary, AB, Canada, Jul. 2009, pp. 1–8.

[80] R. Majumder, B. Chaudhuri, A. Ghosh, R. Majumder, G. Ledwich, and F. Zare, "Improvement of stability and load sharing in an autonomous microgrid using supplementary droop control loop," *IEEE Trans. Power Syst.*, vol. 25, no. 2, pp. 796–808, May 2010.

[81] R. Majumder, G. Ledwich, A. Ghosh, S. Chakrabarti, and F. Zare, "Droop control of converter-interfaced microsources in rural distributed generation," *IEEE Trans. Power Del.*, vol. 25, no. 4, pp. 2768–2778, Oct. 2010.

[82] T. Vandoorn, B. Meersman, L. Degroote, B. Renders, and L. Vandevelde, "A control strategy for islanded microgrids with DC-link voltage control," *IEEE Trans. Power Del.*, vol. 26, no. 2, pp. 703–713, Apr. 2011.

[83] T. L. Vandoorn, B. Renders, L. Degroote, B. Meersman, and L. Vandevelde, "Active load control in islanded microgrids based on the grid voltage," *IEEE Trans. Smart Grid*, vol. 2, no. 1, pp. 139–151, Mar. 2011.

[84] T. L. Vandoorn, J. D. Kooning, B. Meersman, J. M. Guerrero, and L. Vandevelde, "Automatic power-sharing modification of P/V droop controllers in low-voltage resistive microgrids," *IEEE Trans. Power Deliv.*, vol. 27, no. 4, pp. 2318–2325, Oct. 2012.

[85] J. M. Guerrero, M. Chandorkar, T.-L. Lee, and P. C. Loh, "Advanced control architectures for intelligent microgrids—Part I: Decentralized and hierarchical control," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1254–1262, Apr. 2013.

[86] C.-T. Lee, C.-C. Chuang, C.-C. Chu, and P.-T. Cheng, "Control strategies for distributed energy resources interface converters in the low voltage microgrid," in *Proc. IEEE Energy Convers. Congr. Expo.*, San Jose, CA, USA, Sep. 2009, pp. 2022–2029.

[87] J. He, Y. W. Li, J. M. Guerrero, F. Blaabjerg, and J. C. Vasquez, "An islanding microgrid power sharing approach using enhanced virtual impedance control scheme," *IEEE Trans. Power Electron.*, vol. 28, no. 11, pp. 5272–5282, Nov. 2013.

[88] Y. Li and Y. W. Li, "Decoupled power control for an inverter based low voltage microgrid in autonomous operation," in *Proc. IEEE 6th Int. Power Electron. Motion Control Conf.*, Wuhan, China, May 2009, pp. 2490–2496.

[89] Y. Li and Y. W. Li, "Power management of inverter interfaced autonomous microgrid based on virtual frequency-voltage frame," *IEEE Trans. Smart Grid*, vol. 2, no. 1, pp. 30–40, Mar. 2011.

[90] E. Rokrok and M. E. Golshan, "Adaptive voltage droop scheme for voltage source converters in an islanded multibus microgrid," *IET Gener., Transmiss. Distrib.*, vol. 4, no. 5, pp. 562–578, May 2010.

[91] J. He and Y. W. Li, "An accurate reactive power sharing control strategy for DG units in a microgrid," in *Proc. 8th Int. Conf. Power Electron. (ECCE Asia)*, Jeju, South Korea, May 2011, pp. 551–556.

[92] J. He and Y. W. Li, "An enhanced microgrid load demand sharing strategy," *IEEE Trans. Power Electron.*, vol. 27, no. 9, pp. 3984–3995, Sep. 2012.

[93] B. Jiang and Y. Fei, "Smart home in smart microgrid: A cost-effective energy ecosystem with intelligent hierarchical agents," *IEEE Trans. Smart Grid*, vol. 6, no. 1, pp. 3–13, Jan. 2015.

[94] C.-T. Lee, C.-C. Chu, and P.-T. Cheng, "A new droop control method for the autonomous operation of distributed energy resource interface converters," *IEEE Trans. Power Electron.*, vol. 28, no. 4, pp. 1980–1993, Apr. 2013.

[95] C.-X. Zhang and Y. Zeng, "Voltage and reactive power control method for distribution grid," in *Proc. IEEE PES Asia–Pacific Power Energy Eng. Conf. (APPEEC)*, Hong Kong, Dec. 2013, pp. 1–6.

[96] C.-T. Lee, R.-P. Jiang, and P.-T. Cheng, "A grid synchronization method for droop-controlled distributed energy resource converters," *IEEE Trans. Ind. Appl.*, vol. 49, no. 2, pp. 954–962, Mar./Apr. 2013.

[97] C. K. Sao and P. W. Lehn, "Control and power management of converter fed microgrids," *IEEE Trans. Power Syst.*, vol. 23, no. 3, pp. 1088–1098, Aug. 2008.

[98] C. K. Sao and P. W. Lehn, "Autonomous load sharing of voltage source converters," *IEEE Trans. Power Del.*, vol. 20, no. 2, pp. 1009–1016, Apr. 2005.

[99] Q.-C. Zhong, "Robust droop controller for accurate proportional load sharing among inverters operated in parallel," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1281–1290, Apr. 2013.

[100] A. Tuladhar, H. Jin, T. Unger, and K. Mauch, "Control of parallel inverters in distributed AC power systems with consideration of line impedance effect," *IEEE Trans. Ind. Appl.*, vol. 36, no. 1, pp. 131–138, Jan./Feb. 2000.

[101] D. J. Perreault, R. L. Selders, and J. G. Kassakian, "Frequency-based current-sharing techniques for paralleled power converters," *IEEE Trans. Power Electron.*, vol. 13, no. 4, pp. 626–634, Jul. 1998.

[102] M. Fusero, A. Tuckey, A. Rosini, P. Serra, R. Procopio, and A. Bonfiglio, "A comprehensive inverter-BESS primary control for AC microgrids," *Energies*, vol. 12, no. 20, p. 3810, Oct. 2019, doi: 10.3390/en12203810.

[103] S. M. Ashabani and Y. A.-R. I. Mohamed, "A flexible control strategy for grid-connected and islanded microgrids with enhanced stability using nonlinear microgrid stabilizer," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1291–1301, Sep. 2012.

[104] X. Xu, X. Zha, and T. Lin, "Small signal stability fuzzy analysis of microgrid based on credibility theory," in *Proc. Asia–Pacific Power Energy Eng. Conf.*, Chengdu, China, Mar. 2010, pp. 1–4.

[105] Y. Liu, L. Guan, F. Guo, J. Zheng, J. Chen, C. Liu, and J. M. Guerrero, "A reactive power-voltage control strategy of an AC microgrid based on adaptive virtual impedance," *Energies*, vol. 12, no. 16, p. 3057, Aug. 2019, doi: 10.3390/en12163057.

[106] H.-H. Huang, C.-Y. Hsieh, J.-Y. Liao, and K.-H. Chen, "Adaptive droop resistance technique for adaptive voltage positioning in boost DC–DC converters," *IEEE Trans. Power Electron.*, vol. 26, no. 7, pp. 1920–1932, Jul. 2011.

[107] S. Augustine, M. K. Mishra, and N. Lakshminarasamma, "Adaptive droop control strategy for load sharing and circulating current minimization in low-voltage standalone DC microgrid," *IEEE Trans. Sustain. Energy*, vol. 6, no. 1, pp. 132–141, Jan. 2015.

[108] C. X. Dou and B. Liu, "Multi-agent based hierarchical hybrid control for smart microgrid," *IEEE Trans. Smart Grid*, vol. 4, no. 2, pp. 771–778, Jun. 2013.

[109] A. Anvari-Moghaddam, A. Rahimi-Kian, M. S. Mirian, and J. M. Guerrero, "A multi-agent based energy management solution for integrated buildings and microgrid system," *Appl. Energy*, vol. 203, pp. 41–56, Oct. 2017.

[110] F. Habibi, A. H. Naghshbandy, and H. Bevrani, "Robust voltage controller design for an isolated microgrid using Kharitonov's theorem and D-stability concept," *Int. J. Electr. Power Energy Syst.*, vol. 44, no. 1, pp. 656–665, Jan. 2013.

[111] D. Y. Yamashita, I. Vechiu, and J.-P. Gaubert, "A review of hierarchical control for building microgrids," *Renew. Sustain. Energy Rev.*, vol. 118, Feb. 2020, Art. no. 109523.

[112] A. Llaria, O. Curea, J. Jiménez, and H. Camblong, "Survey on microgrids: Unplanned islanding and related inverter control techniques," *Renew. Energy*, vol. 36, no. 8, pp. 2052–2061, Aug. 2011.

[113] S. Ahmad, A. Ahmad, M. Naeem, W. Ejaz, and H. Kim, "A compendium of performance metrics, pricing schemes, optimization objectives, and solution methodologies of demand side management for the smart grid," *Energies*, vol. 11, no. 10, p. 2801, Oct. 2018, doi: 10.3390/en11102801.

[114] A. M. Bouzid, J. M. Guerrero, A. Cheriti, M. Bouhamida, P. Sicard, and M. Benghanem, "A survey on control of electric power distributed generation systems for microgrid applications," *Renew. Sustain. Energy Rev.*, vol. 44, pp. 751–766, Apr. 2015.

[115] D. Abdellatif, R. AbdelHady, A. M. Ibrahim, and E. A. El-Zahab, "Conditions for economic competitiveness of pumped storage hydroelectric power plants in Egypt," *Renew., Wind, Water, Sol.*, vol. 5, no. 1, pp. 1–14, Mar. 2018, doi: 10.1186/s40807-018-0048-1.

[116] A. Elmouatamid, R. Ouladsine, M. Bakhouya, N. E. Kamoun, M. Khaidar, and K. Zine-Dine, "Review of control and energy management approaches in micro-grid systems," *Energies*, vol. 14, no. 1, p. 168, Dec. 2020, doi: 10.3390/en14010168.

[117] A. Singh and S. Suhag, "Trends in islanded microgrid frequency regulation—A review," *Smart Sci.*, vol. 7, no. 2, pp. 91–115, Apr. 2019.

[118] S. Hajiaghasi, A. Salemnia, and M. Hamzeh, "Hybrid energy storage system for microgrids applications: A review," *J. Energy Storage*, vol. 21, pp. 543–570, Feb. 2019.

[119] Z. A. Arfeen, A. B. Khairuddin, R. M. Larik, and M. S. Saeed, "Control of distributed generation systems for microgrid applications: A technological review," *Int. Trans. Electr. Energy Syst.*, vol. 29, no. 9, 2019, Art. no. e12072, doi: 1002/2050-7038.12072.

[120] W. Jing, C. Hung Lai, S. H. W. Wong, and M. L. D. Wong, "Battery-supercapacitor hybrid energy storage system in standalone DC microgrids: Areview," *IET Renew. Power Gener.*, vol. 11, no. 4, pp. 461–469, Mar. 2017.

[121] M. Carpintero-Rentería, D. Santos-Martín, and J. M. Guerrero, "Microgrids literature review through a layers structure," *Energies*, vol. 12, no. 22, p. 4381, Nov. 2019, doi: 10.3390/en12224381.

[122] X. Wei, X. Xiangning, and C. Pengwei, "Overview of key microgrid technologies," *Int. Trans. Electr. Energy Syst.*, vol. 28, no. 7, p. e2566, Mar. 2018, doi: 10.1002/etep.2566.

[123] J. Hu, Y. Shan, J. M. Guerrero, A. Ioinovici, K. W. Chan, and J. Rodriguez, "Model predictive control of microgrids—An overview," *Renew. Sustain. Energy Rev.*, vol. 136, Feb. 2021, Art. no. 110422.

[124] J. M. Carrasco, L. G. Franquelo, J. T. Bialasiewicz, E. Galvan, R. C. PortilloGuisado, M. A. M. Prats, J. I. Leon, and N. Moreno-Alfonso, "Power-electronic systems for the grid integration of renewable energy sources: A survey," *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1002–1016, Jun. 2006.

[125] J. Urquizo, P. Singh, N. Kondrath, R. Hidalgo-Leon, and G. Soriano, "Using D-FACTS in microgrids for power quality improvement: A review," in *Proc. IEEE 2nd Ecuador Tech. Chapters Meeting (ETCM)*, Salinas, Ecuador, Oct. 2017, pp. 1–6.

[126] M. T. L. Parimi and A. V. P. Kumar, "A review of reactive power compensation techniques in microgrids," *Renew. Sustain. Energy Rev.*, vol. 81, pp. 1030–1036, Jan. 2018.

[127] D. Gutierrez-Rojas, P. H. J. Nardelli, G. Mendes, and P. Popovski, "Review of the state of the art on adaptive protection for microgrids based on communications," *IEEE Trans. Ind. Informat.*, vol. 17, no. 3, pp. 1539–1552, Mar. 2021.

[128] L. Zhang, N. Tai, W. Huang, J. Liu, and Y. Wang, "A review on protection of DC microgrids," *J. Mod. Power Syst. Clean Energy*, vol. 6, no. 6, pp. 1113–1127, 2018.

[129] S. Mirsaeidi, D. M. Said, M. W. Mustafa, M. H. Habibuddin, and K. Ghaffari, "Progress and problems in micro-grid protection schemes," *Renew. Sustain. Energy Rev.*, vol. 37, pp. 834–839, Sep. 2014.

[130] A. Chandra, G. K. Singh, and V. Pant, "Protection techniques for DC microgrid—A review," *Electr. Power Syst. Res.*, vol. 187, Oct. 2020, Art. no. 106439, doi: 10.1016/j.epsr.2020.106439.

[131] L. Che, M. E. Khodayar, and M. Shahidehpour, "Adaptive protection system for microgrids: Protection practices of a functional microgrid system," *IEEE Electrific. Mag.*, vol. 2, no. 1, pp. 66–80, Mar. 2014.

[132] A. Dagar, P. Gupta, and V. Niranjan, "Microgrid protection: A comprehensive review," *Renew. Sustain. Energy Rev.*, vol. 149, Oct. 2021, Art. no. 111401.

[133] A. A. Salam, A. Mohamed, and M. A. Hannan, "Technical challenges on microgrids," *ARPN J. Eng. Appl. Sci.*, vol. 3, pp. 64–69, Jan. 2008.

[134] R. Zamora and A. K. Srivastava, "Controls for microgrids with storage: Review, challenges, and research needs," *Renew. Sustain. Energy Rev.*, vol. 14, no. 7, pp. 2009–2018, Sep. 2010.

[135] W. Bower, D. Ton, R. Guttromson, S. Glover, J. Stamp, D. Bhatnagar, and J. Reilly, "The advanced microgrid: Integration and interoperability," Sandia Nat. Lab., Livermore, CA, USA, Tech. Rep., Mar. 2014.

[136] J. Joy, D. E. Jasmin, and V. R. John, "Challenges of smart grid," *Int. J. Adv. Res. Electr., Electron. Instrum. Eng.*, vol. 2, no. 3, pp. 976–981, Mar. 2013.

[137] C. P. Vineetha and C. A. Babu, "Smart grid challenges, issues and solutions," in *Proc. Int. Conf. Intell. Green Building Smart Grid (IGBSG)*, Taipei, Japan, Apr. 2014, pp. 1–4.

[138] A. Gaviano, K. Weber, and C. Dirmeier, "Challenges and integration of PV and wind energy facilities from a smart grid point of view," *Energy Proc.*, vol. 25, pp. 118–125, Jan. 2012.

[139] S. S. Rath, G. Panda, P. K. Ray, and A. Mohanty, "A comprehensive review on microgrid protection: Issues and challenges," in *Proc. 3rd Int. Conf. Energy, Power Environ., Towards Clean Energy Technol.*, Shillong, India, Mar. 2021, pp. 1–6.

[140] J. J. Justo, F. Mwasilu, J. Lee, and J.-W. Jung, "AC-microgrids versus DC-microgrids with distributed energy resources: A review," *Renew. Sustain. Energy Rev.*, vol. 24, pp. 387–405, Aug. 2013.

[141] E. Planas, J. Andreu, J. I. Gárate, I. M. de Alegría, and E. Ibarra, "AC and DC technology in microgrids: A review," *Renew. Sustain. Energy Rev.*, vol. 43, pp. 726–749, Mar. 2015.

[142] M. Stadler, G. Cardoso, S. Mashayekh, T. Forget, N. DeForest, A. Agarwal, and A. Schönbein, "Value streams in microgrids: A literature review," *Appl. Energy*, vol. 162, pp. 980–989, Jan. 2016.

[143] M. Soshinskaya, W. H. J. Crijns-Graus, J. M. Guerrero, and J. C. Vasquez, "Microgrids: Experiences, barriers and success factors," *Renew. Sustain. Energy Rev.*, vol. 40, pp. 659–672, Dec. 2014.

[144] A. Kumar and M. L. Azad, "Challenges in recent microgrid systems: A review," *Int. J. Adv. Eng. Tech.*, vol. 8, no. 2, pp. 203–210, 2015.

[145] M. Boork, M. Thomtén, M. Brolin, M. Uyterlinde, K. Straver, C. Kraan, K. Hegermann, E. Laes, O. Valkering, and S. Maggiore, "Key success factors and barriers to end user engagement in smart grid projects," in *Proc. BEHAVE Energy Conf.*, Oxford, U.K., 2014, pp. 3–4.

[146] A. Molderink, V. Bakker, M. G. C. Bosman, J. L. Hurink, and G. J. M. Smit, "Management and control of domestic smart grid technology," *IEEE Trans. Smart Grid*, vol. 1, no. 2, pp. 109–119, Sep. 2010.

[147] M. Vasirani and S. Ossowski, "Smart consumer load balancing: State of the art and an empirical evaluation in the Spanish electricity market," *Artif. Intell. Rev.*, vol. 39, no. 1, pp. 81–95, Jan. 2013.

[148] Z. Shuai, Y. Sun, Z. J. Shen, W. Tian, C. Tu, Y. Li, and X. Yin, "Microgrid stability: Classification and a review," *Renew. Sustain. Energy Rev.*, vol. 58, pp. 79–167, May 2016.

[149] M. A. Zamani, T. S. Sidhu, and A. Yazdani, "A protection strategy and microprocessor-based relay for low-voltage microgrids," *IEEE Trans. Power Del.*, vol. 26, no. 3, pp. 1873–1883, Jul. 2011.

[150] S. R. Samantaray, G. Joos, and I. Kamwa, "Differential energy based microgrid protection against fault conditions," in *Proc. IEEE PES Innov. Smart Grid Technol. (ISGT)*, Washington, DC, USA, Jan. 2012, pp. 1–7.

[151] H. Nikkhajoei and R. H. Lasseter, "Microgrid fault protection based on symmetrical and differential current components," Lawrence Berkeley Nat. Lab., California Energy Commun., Berkeley, CA, USA, Tech. Rep., 2006.

[152] N. Schaefer, T. Degner, A. Shustov, T. Keil, and J. Jaeger, "Adaptive protection system for distribution networks with distributed energy resources," in *Proc. 10th IET Int. Conf. Develop. Power Syst. Protection (DPSP)*, Manchester, U.K., 2010, pp. 1–5.

[153] N. Jayawarna and M. Barnes, "Central storage unit response requirement in 'good citizen' microgrid," presented at the 13th Eur. Conf. Power Electron. Appl. (EPE), Barcelona, Spain, 2009.

[154] M. E. Khodayar, M. Barati, and M. Shahidehpour, "Integration of high reliability distribution system in microgrid operation," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 1997–2006, Dec. 2012.

[155] Z. Wang and J. Wang, "Self-healing resilient distribution systems based on sectionalization into microgrids," *IEEE Trans. Power Syst.*, vol. 30, no. 6, pp. 3139–3149, Nov. 2015.

[156] A. Khodaei, "Microgrid optimal scheduling with multi-period islanding constraints," *IEEE Trans. Power Syst.*, vol. 29, no. 3, pp. 1383–1392, May 2014.

[157] M. Mahmoodi, P. Shamsi, and B. Fahimi, "Economic dispatch of a hybrid microgrid with distributed energy storage," *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 2607–2614, Nov. 2015.

[158] A. Khodaei and M. Shahidehpour, "Microgrid-based co-optimization of generation and transmission planning in power systems," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 1582–1590, May 2013.

[159] C. Ahn and H. Peng, "Decentralized voltage control to minimize distribution power loss of microgrids," *IEEE Trans. Smart Grid*, vol. 4, no. 3, pp. 1297–1304, Sep. 2013.

[160] C. N. Papadimitriou, V. A. Kleftakis, and N. D. Hatziargyriou, "A novel islanding detection method for microgrids based on variable impedance insertion," *Electr. Power Syst. Res.*, vol. 121, pp. 58–66, Apr. 2015.

[161] X. Fang, S. Misra, G. Xue, and D. Yang, "Smart grid—The new and improved power grid: A survey," *IEEE Commun. Surveys Tuts.*, vol. 14, no. 4, pp. 944–980, 4th Quart., 2012.

[162] H. Gharavi and R. Ghafurian, "Smart grid: The electric energy system of the future [scanning the issue]," *Proc. IEEE*, vol. 99, no. 6, pp. 917–921, Jun. 2011, doi: 10.1109/JPROC.2011.2124210.

[163] I. Colak, "Introduction to smart grid," in *Proc. Int. Smart Grid Workshop Certificate Program (ISGWCP)*, Mar. 2016, pp. 1–5.

[164] A. M. Annaswamy and M. Amin, *IEEE Vision for Smart Grid Controls: 2030 and Beyond*, Standard, Jun. 2013, pp. 1–168, doi: 10.1109/IEEESTD.2013.6577608.

[165] T. L. Vandoorn and L. Vandevelde, "Contribution of microgrids to the development of the smart grid," in *Smart Grids: Clouds, Communications, Open Source, and Automation*, 1st ed. Boca Raton, FL, USA: CRC Press, 2014, ch.9, pp. 191–211, doi: 10.1201/b16908.

[166] M. J. Davison, T. J. Summers, and C. D. Townsend, "A review of the distributed generation landscape, key limitations of traditional microgrid concept & possible solution using an enhanced microgrid architecture," in *Proc. IEEE Southern Power Electron. Conf. (SPEC)*, Puerto Varas, Chile, Dec. 2017, pp. 1–6.

[167] A. Hirsch, Y. Parag, and J. Guerrero, "Microgrids: A review of technologies, key drivers, and outstanding issues," *Renew. Sustain. Energy Rev.*, vol. 90, pp. 402–411, Jul. 2018.

[168] A. M. Jadhav, N. R. Patne, and J. M. Guerrero, "A novel approach to neighborhood fair energy trading in a distribution network of multiple microgrid clusters," *IEEE Trans. Ind. Electron.*, vol. 66, no. 2, pp. 1520–1531, Feb. 2019.

[169] P. G. Da Silva, D. Ilic, and S. Karnouskos, "The impact of smart grid prosumer grouping on forecasting accuracy and its benefits for local electricity market trading," *IEEE Trans. Smart Grid*, vol. 5, no. 1, pp. 402–410, Jan. 2014.

[170] K. Kok and S. Widergren, "A society of devices: Integrating intelligent distributed resources with transactive energy," *IEEE Power Energy Mag.*, vol. 14, no. 3, pp. 34–45, May/Jun. 2016.

[171] Y. Zhou, J. Wu, and C. Long, "Evaluation of peer-to-peer energy sharing mechanisms based on a multiagent simulation framework," *Appl. Energy*, vol. 222, pp. 993–1022, Jul. 2018.

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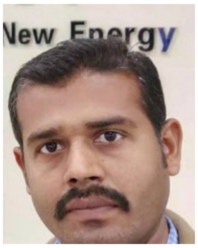

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