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Review

A Comprehensive Review on Integration Challenges, Optimization Techniques and Control Strategies of Hybrid AC/DC Microgrid

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Abstract: The depletion of natural resources and the intermittence of renewable energy resources have pressed the need for a hybrid microgrid, combining the benefits of both AC and DC microgrids, minimizing the overall deficiency shortcomings and increasing the reliability of the system. The hybrid microgrid also supports the decentralized grid control structure, aligning with the current scattered and concentrated load scenarios. Hence, there is an increasing need to explore and reveal the integration, optimization, and control strategies regarding the hybrid microgrid. A comprehensive study of hybrid microgrid's performance parameters, efficiency, reliability, security, design flexibility, and cost-effectiveness is required. This paper discusses major issues regarding the hybrid microgrids, the integration of AC and DC microgrids, their security and reliability, the optimization of power generation and load management in different scenarios, the efficient management regarding uncertainty for renewable energy resources, the optimal placement of feeders, and the cost-effective control methodologies for the hybrid microgrid. The major research areas are briefly explained, aiming to find the research gap that can further improve the performance of the grid. In light of the recent trends in research, novel strategies are proposed that are found most effective and cost-friendly regarding the hybrid microgrid. This paper will serve as a baseline for future research, comparative analysis, and further development of novel techniques regarding hybrid microgrids.

Keywords: microgrids; system integration; optimal scheduling; optimization methods; power system control

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1. Introduction

The energy demand in the last few decades has increased drastically due to increased population, high living standards, and infrastructural development. As a result, high penetration of traditional generating units and better efficiency of a power system are required. However, the depleting fossil fuels, high consumption rate, environmental implications of traditional energy sources, inefficiency, and aging of power systems have created an unsustainable system that needs to be modified. In this context, the popularity of renewable energy sources has increased over the years [1].

Renewable energy sources include solar, wind, tidal energy, biofuel, fuel cells, and small hydro plants free from CO_2 emissions and available abundantly. They are also called distributed energy resources, as they are usually connected at the distribution level. The integration of distributed energy resources with a utility grid is an attractive solution, but reliable cost-effective integration still remains a challenge. The smart grid is the most promising solution as a next-generation power system encompassing clusters of interconnected micro-grids [2].

A microgrid is a combination of a low voltage distribution system with distributed generation, energy storage systems, and loads. It is the most excellent solution to achieve the decentralization of a power system. The inherent flexibility of a microgrid to be connected/disconnected from the main grid gives an improved system with reliability, less investment cost, the green effect due to renewable sources, improved power quality of a system, and reduces the losses of distribution network. A microgrid can be divided into three major groups based on topology, namely, AC, DC, and hybrid. AC microgrid is the most used configuration which incorporates existing grid infrastructure, protection, and technologies. However, the need for synchronization of distributed generation (DG) units and losses resulting from reactive power circulation are its drawbacks. Moreover, the presence of DC sources presents the problem of conversion into AC using converters which decreases the overall efficiency. The increased penetration of DC-based distributed energy resources such as PV and fuel cells, energy storage systems, and loads has paved the way for DC microgrids. However, it requires a considerable modification of the available power network. Both individual AC and DC microgrids suffer from inefficiency due to multiple DC/DC, AC/DC, and DC/AC conversions. A hybrid microgrid is an excellent solution for the realization of smart grids in conventional distribution networks. It combines the advantages of both AC and DC microgrids allowing direct integration of AC and DC-based distributed energy resources, energy storage systems and loads, no synchronization, simple transformation, and economic feasibility [3–6]. Among the various meanings of hybrid microgrid, we mainly intend "hybrid microgrid" as "an integrated AC/DC low voltage microgrid system" or "a hybrid low-voltage microgrid, unless otherwise specified."

The hybrid microgrid comprises vast areas for research. For any further research, a detailed literature review regarding the latest developments in the field of a hybrid microgrid is required. The review papers make this task easier by summarizing the studies and enabling the reader to identify the existing research gaps. This paper collectively provides a review of research regarding all the major areas of hybrid microgrids, starting from the topology and leading to optimization techniques and control methodologies employed in it. The uniqueness of this review paper is that it provides a comprehensive comparison of this review paper with other reviews of the hybrid microgrid written regarding all the major sections, e.g., challenges, optimization, power generation, and sharing control. This makes it the ultimate paper that covers the essential information for the researchers to traverse the research horizons further.

The existing challenges regarding the hybrid microgrid, with a comparison of feasible solutions and the degree of research focused on each solution, are highlighted by this paper. It will not only help to identify the references for any focused topic quickly but also present the latest trends and the research gaps left regarding the hybrid microgrid. It is incumbent to have this meticulous knowledge to serve as a light for the pathway leading to future research.

This paper can be divided into six sections. Section 1 gives a brief introduction regarding the survey of the hybrid microgrid. Section 2 discusses the structure of a hybrid AC/DC microgrid. In Section 3, the key issues and challenges in the integration of microgrids are observed. Section 4 covers the classification and details of optimization techniques being employed for the hybrid microgrids. Section 5 presents the coordination control techniques. Section 6 compares this review paper with other recent surveys regarding the hybrid microgrid, and Section 7 concludes the study.

The main contributions of this paper are as follows:

Objective 1: The paper discusses the integration of AC and DC subgrids and the use of interlinking converters. It unites the recent studies regarding the interlinking converters and aims to summarize the findings of the most researched section of integration and the existing research gap and latest trend in this field.

Objective 2: It emphasizes the protection of the hybrid microgrid and sums up the latest techniques used for protection and evaluates their performance in different operational scenarios of the hybrid microgrid.

Objective 3: The paper presents a critical analysis of all the optimization techniques employed in hybrid microgrids regarding power flow, power generation, minimizing the uncertainty issues, and the design and topology of the hybrid microgrid. It also finds the recent trends in optimization techniques, finds the efficiency of each area of techniques used, and suggests the latest areas of research where significant progress can be achieved regarding hybrid microgrids.

Objective 4: The control methods for power flow and generation, as an important aspect of hybrid microgrid, are taken into understudy for this review. It encompasses all the recent control methodologies and proposes novel strategies which are being researched and found more cost-effective.

Objective 5: The paper presents a comprehensive comparative analysis with the existing surveys in all the relevant fields and establishes a novel framework regarding the review of all the major research studies in one paper.

2. Structure of Hybrid AC/DC Microgrid

A typical hybrid microgrid structure consists of an AC network, DC network, utility grid, and interface stage. Hybrid AC/DC microgrid incorporates both individual AC and DC microgrids through interfacing stages. Based on the connection of distributed generators and energy storage systems to the main bus and interconnection of the main bus with the utility grid, the hybrid microgrid can be divided into three topologies such as AC coupled, DC coupled, and AC-DC coupled. The major difference between them is the nature of the main grid present [7]. In [8], the authors compare different batteries for optimal operation of renewable energy resources in a hybrid microgrid with the help of iHOGA software. It shows that the existing techniques for life span prediction of batteries are not accurate, and comparatively, the lithium batteries exhibit less cost of energy. A more detailed discussion of power management schemes of hybrid AC/DC microgrid encompassing the DC and AC sources/loads is presented in [9].

2.1. AC Coupled Hybrid Microgrid

In AC coupled microgrid, as shown in Figure 1, distributed generators, energy storage systems, and utility are connected to the main AC bus. The connection of the energy storage system and DC loads is done through bidirectional interfacing converters. It is the most frequently used topology worldwide due to its simplicity and availability of AC generation systems. However, interfacing converters account for the existing inefficiency in this topology.

2.2. DC Coupled Hybrid Microgrid

In the DC-coupled microgrid, as shown in Figure 1, distributed generators, energy storage element, and load are connected, and the main DC bus interfacing converter is used for the connection of AC distributed generators with the main grid.

2.3. AC-DC Coupled Hybrid Microgrid

In this topology, as shown in Figure 1, both AC and DC buses are connected with Distributed generators, energy storage systems, and load. The interlinking converters have been employed as an interface between AC and DC subgrids. This configuration limits higher interfacing, which in turn reduces the cost and enhances the overall efficiency. This topology is the most attractive solution for a paradigm of future smart grids.

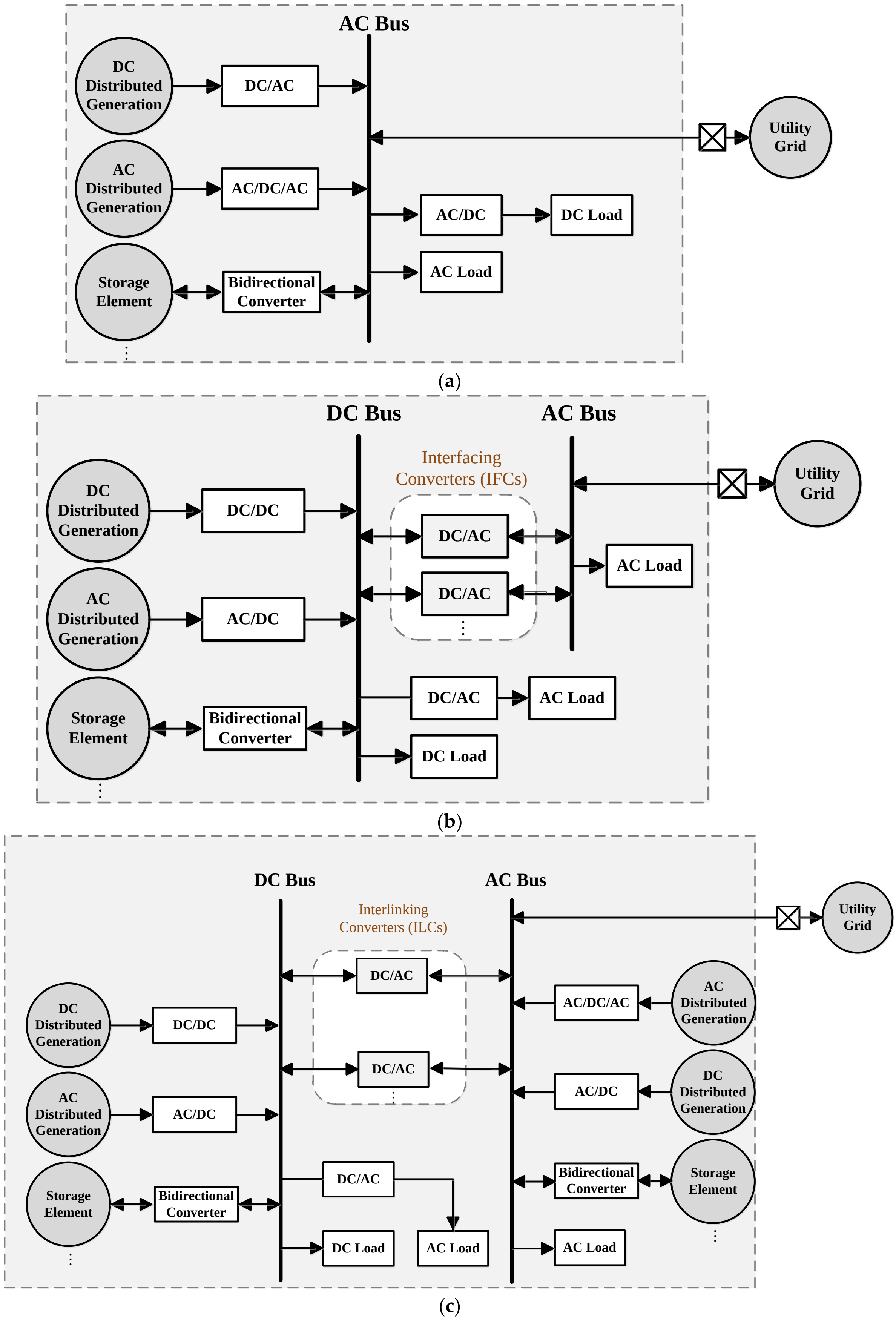

Figure 1. (**a**) AC coupled, (**b**) DC coupled, and (**c**) AC-DC coupled hybrid microgrid [9].

3. Challenges and Issues in Hybrid AC/DC Microgrid

A hybrid AC/DC microgrid is the next step in realizing smart grid paradigms and decentralized power systems. It has numerous advantages as compared to existing microgrids and utilities. However, there are many practical challenges, such as operational issues, coordination control, protection issues, stability, energy management system, communication infrastructure, and market trends in achieving efficient and feasible future networks. The challenges of hybrid AC/DC microgrids are summarized in Figure 2 and are addressed as follows.

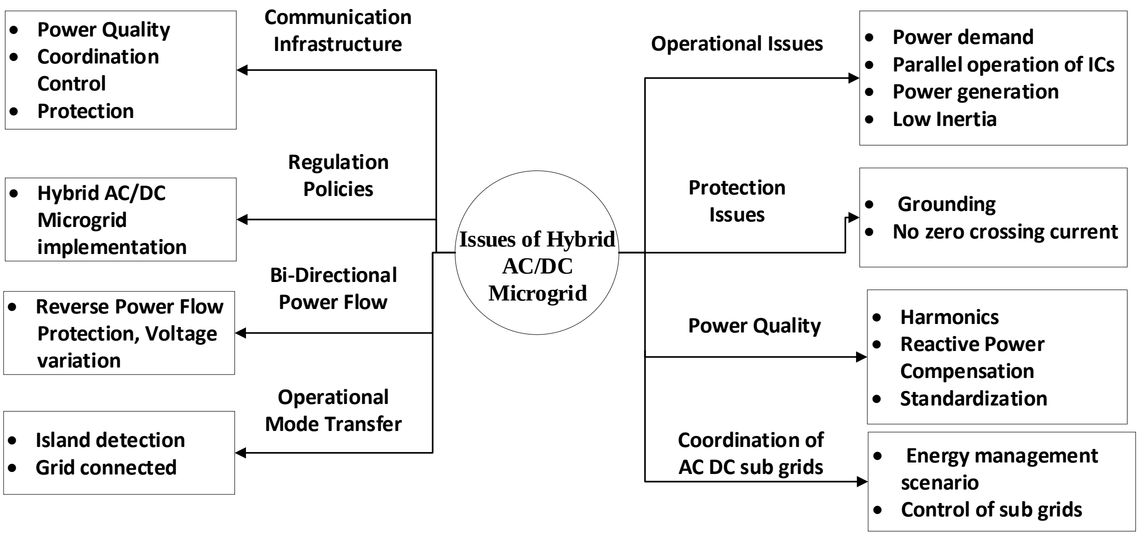

Figure 2. Challenges of hybrid AC/DC microgrid.

3.1. Operational Challenges

The AC and DC subgrids are tied through interlinking converters and bidirectional power-sharing, which ensures the stability of the network. A hybrid microgrid works in two modes of operation: grid-connected and islanded. In islanded mode, the lack of frequency support to the AC sub-system and the absence of voltage support to the DC sub-system makes the stability of a hybrid microgrid the most important issue to be addressed. The major operational challenges for hybrid AC-DC microgrids have been listed below.

Power-sharing under different operational conditions is a major issue regarding the stability of hybrid microgrids. It is dependent not only on the AC sub-system but also on the DC sub-system due to the power exchange across the interfacing converter. Many research articles have investigated the power-sharing in hybrid microgrids based on the droop control for all distributed generators. In [10], the authors present the operation of a hybrid AC/DC microgrid where the droop scheme is designed to control the converter operation and losses during unloaded and heavily loaded scenarios. It was found that the power shared affects the dynamics of AC and DC subgrids, creating a stability issue for the whole system. Moreover, the use of a single converter decreases the reliability of the system. In [11], the authors demonstrate the idea of multiple converters to increase system reliability. Still, the drawback is that it makes the AC sub-grid more susceptible to power changes, decreasing the overall performance. In [12], the authors propose the usage of an energy storage system to improve power transfer between sub-grids.

The parallel operation of multiple interlinking converters is another important challenge. The operation of converters has many advantages such as improved reliability of the system, low rating converter for high power applications, etc. However, parallel ICs operation generates serious issues such as non-linear load behavior of converters, re-synchronization required after different grid operational modes, and the circulating current issue between parallel operation [13].

A large gap between generation and load can lead to voltage and frequency problems because microgrids have the tendency to transition between grid-connected mode and islanded mode. Due to the interconnection of a large number of distributed generators, "plug and play" can be a serious problem. The generation and load uncertainties are a big challenge to the optimal dispatch and operation of a microgrid. Much research is needed for the usage of stochastic optimization to resolve these uncertainties, and these techniques must also include the impact of interlinking converters on overall optimization. A robust optimization model also needs to be developed for the operation of microgrids [14].

Another critical aspect of the operation of hybrid microgrids is the control and load management strategy during islanded and grid-tied connections, discussed in detail in the last section of this paper.

3.2. Power Quality Issues

Power quality challenges are more dominant in the future in hybrid microgrids due to the integration of single-phase/unbalanced load, unbalanced distributed generations, and non-linear loads. The penetration of Distributed generators in the network produces many quality issues such as voltage fluctuations, harmonic distortion, voltage surges, and frequency deviations. Moreover, the variable output of distributed generators produces a reverse power flow problem. These issues of power quality amplify in the case of hybrid microgrids. The system power quality is the most critical issue regarding the operation and falls in the categories of harmonics, reactive power compensation, and standardization of technical and commercial protocols [15].

Owing to the intense integration of distributed generation units, in the power system due to nonlinear power electronics devices, harmonics are introduced. The three-phase unbalanced loads cause a large negative sequence current that increases the losses of the system, reducing the overall efficiency of the entire system. Hence, in order to address this problem, some filtering techniques should be applied to make a pollution-free system. In [16], the authors present harmonic compensation using interfacing and interlinking converters, where the harmonic control is performed by converter at different frequencies, power rating, and filter design. Bidirectional AC/DC converters of hybrid grid normally are voltage sources and have smart functions of self-commutation and the ability to provide reactive power. It avoids voltage sag in a system [17].

In a hybrid microgrid, the DC side has the edge over the AC but still faces several problems because it is in the growing stage. Therefore, the DC side requires further work to standardize the DC grid and its voltage level. One of the key issues is the lack of adequate equipment and standards for DC power distribution.

3.3. Communication Challenges

Communication is a big challenge in order to achieve a reliable and efficient system because communication significantly affects its design, such as topology, operational mode, coordination control of hybrid grid system, its protection schemes, control requirements of the system, and power management. Many different types of communication have been adopted to fulfill reliable and efficient operations, such as wireless and optical fiber. The hybrid microgrid is generally classified into two categories the communication-based system and the other communication less system. For control and power management, the communication-based system provides information regarding voltage, current, and frequency to determine the operation of a distributed system. Communication is most important for the protection of hybrid systems as well as power control [18].

The design of a communication system between the interlinked converter of a hybrid AC-DC microgrid system is a crucial step. Effective communication between different components to control and monitor in real-time is a big challenge. The development of hybrid microgrids as an integral part of a smart grid system requires intelligent coordination among controllers of the system, protection of the system, and the most important communication.

Communication regarding coordination is the most important aspect of communication challenges. In the future grid composed of intelligent electronics devices with high complexity, the design of reliable communication and the standardization of the system holds a higher priority [19].

For the improved performance of control and protection coordination control, attention must be paid to develop proper infrastructure for communication between components to coordinate and perform an action. The different types of applicable standards are IEC 61850 standard, ANSI C12.22 standard, IEC 61499 standard, and IEC 61850 standard.

Another important aspect is the communication regarding the control of the system. In hybrid microgrids, the system protection in both AC and DC has some issues such as self-healing of system, grounding, and no zero-crossing current in DC side which operates the circuit breaker. Therefore, to integrate a control system with protection, well-established communication infrastructure is required [20,21].

Regulation is critical regarding the facilitation of microgrid structures. The practical implementation of hybrid microgrids needs to consider the regulatory issues and key drivers. Regulation is the combination of standards and guidance about distributed energy resources interconnections and integration with the main utility grid. In the case of hybrid AC/DC microgrid, the regulation needs to be further studied as the current regulatory process for AC network is already complex enough due to a combination of existing rules and standards that are not microgrid friendly. Therefore, there is a need for a clear regulatory framework that may include operations, interconnection, and different operating modes; all of these are reviewed in the following sections. The most common challenge for the interconnection of microgrids with the main grid is the connection cost for private microgrid inverters [22]. Moreover, the islanded operation of hybrid AC/DC microgrids poses a conflict with present rules and requires further research. Secondly, the installation of bidirectional energy meters to record energy transfer is another challenge [23]. Reference [24] provides a comparative assessment of regulatory challenges faced by different microgrid models, namely, distribution system operator (DSO) model, hybrid model, and third-party model. It is concluded that the hybrid model administrated by DSO still faces regulatory challenges pertaining to command-and-control instruments (liabilities and ensuring the security of supply and environmental and siting laws), economic instruments (tax collection, tariffs, and RE subsidies), and informational instruments (customer interaction and right of choice and metering arrangements).

In [25], the authors set different social, economic, environmental, technical, and institutional parameters and envision different generation technologies of hybrid microgrids, in light of these parameters.

4. Optimization Techniques

The increasing demand for renewable energy resources due to the development of semiconductors and feasible access in remote areas, coupled with the depleting fossil fuel resources and awareness of environmental protection has led to an intense injection of renewable energy resources in an existing microgrid. The hybrid microgrid serves as a gateway to enhance the system properties and performance parameters regarding the issues mentioned above. It supports the local energy demands with enhanced reliability, power quality, system stability and couples the AC and DC loads, minimizing the conversion losses. This section comprises articles related to optimization techniques for solving problems regarding the hybrid AC DC microgrid. The problems are broadly classified as power flow optimization, uncertainty optimization, and design optimization.

4.1. Optimization Techniques Regarding Power Flow

The operation of a microgrid is studied and enhanced using modern algorithms to achieve the optimal power flow, with the main aim to reduce losses and minimize the cost. The complex power in each node of a power system has a real active part and an imaginary reactive part, and the voltage magnitude and angles on these nodes are adjusted to meet the desired results. A large number of DC equipment and converters with more complex power characteristics and modern control algorithms add to the difficulty in the modeling of power flow. It is the need of the hour to develop the steady-state model for new devices such as DC transformers, PET (power electronic transformer), and distributed generators. The latest research in this field has been summarized below.

In [26], the authors focus on the maximization of renewable energy usage and the minimization of the operational cost of a hybrid AC-DC microgrid. It stresses the need for load coordination of the source network and uses an improved memetic algorithm (IMA) which gives shorter running time and excelled results compared to the basic memetic algorithm. In [27], the authors apply a multi-objective particle swarm optimization technique which achieves a good configuration and sizing of the proposed system of PV, wind, battery, and fuel cell for remote areas. It employs supervisory control and fuzzy logic control with input and output membership functions for battery charging and discharging. In [28], the authors propose new equipment, a power electronic transformer (PET), and a decentralized model for optimum power flow to attain the autonomous operation with the help of voltage source converter power injection control and kriging model. It decomposes the optimal power flow problem of hybrid microgrid using the analytic target cascading (ATC). It shows that the Kriging model of PET with ATC gives better fitting accuracy to loss characteristic functions, has low communication requirements, and can solve decentralized and centralized power flow problems on a large scale.

In [29], the authors employ fuzzy logic to meet the load demand, monitor battery charging and discharging, and optimize the cost of operation considering the high penetration of renewable energy resources in the hybrid grid. In [30], the authors propose the fuzzy logic system for cost and emission optimization using optimal droop control values. It compares the particle swarm optimization algorithm (PSO) and multi-objective genetic algorithm (GA) and finds that later gives results in close proximity comparatively. In [31], the authors deal with the increase in interaction between electrical and thermal energy with the help of an energy hub embedded in a hybrid microgrid. A two-stage stochastic problem based on optimization is formulated by using a sample average approximation mechanism. The decomposition technique (Bender) is used to solve multiple cases generated by this mechanism. In this technique, the cost of the grid is minimized. By using the heating and cooling systems, the operational efficiency of the energy hub can be increased. In [32], the authors introduce a novel dynamic power routing (DPR) technique for the operation of islanded AC-DC hybrid microgrid. This work can be summarized as introducing a novel DPR technique, integrating it with a controller supervisory, which uses a generic algorithm to minimize load-shedding. The results demonstrate the enhancement of system reliability. In [33], the authors target the increase in steady-state stability by optimum power flow (OPF) by using the Interior Point (IP) method. The presented AC/DC optimal power flow (OPF) can be used to discover the challenges (technical and economic) associated with a hybrid microgrid. It results in the optimization of droop parameters of energy resources and interlinking of the converters to maximize system load-ability.

In [34], the authors propose the optimal operation under the spot price method to ensure the economic benefit of the hybrid microgrid. This technique is also used for power balancing, which helps to maximize profit. This model has many benefits as it can increase revenue and reduce operating costs. In [35], the authors propose the probabilistic economic dispatch (ED) tool for energy management of hybrid microgrids. The energy management technique is presented to provide a consistent supply at a low cost. In [36], the authors highlight the impact of plugin hybrid electric vehicles (PHEVs) on the hybrid microgrid, and a novel technique is employed for the optimal operation of renewable resources. The system is modeled using MILP and GAMS software and is used to minimize the operational cost.

In [37], the authors propose a new compartmentalization strategy for the optimal economic operation of hybrid microgrids, where the microgrids are divided into several nanogrids. Each of the nanogrids is optimized with respect to optimal power-sharing, using pinning synchronization and utility cost, leading to the optimization of the overall system. In [38], the authors propose a novel optimization model based on multileader and multifollower game theory to tackle the power imbalance in the three-phase hybrid microgrid emerging due to massive integration and independent operation of the subgrids. In [39], the authors employ HOMER software to model the hybrid microgrid with available energy resources in Pakistan and minimize the cost of energy and environmental emissions. In [40], the authors signify the reduction of operational cost of the hybrid microgrid with the help of particle swarm optimization technique. The authors show the detailed working of the algorithm, and the comparison with older studies also reveals the significance of this technique to minimize the operational cost. In [41], the authors propose a novel economic load dispatch technique for the hybrid microgrid considering the nonlinear characteristics of the problem. The authors employ the Multi-Objective Spotted Hyena and Emperor Penguin Optimization (MOSHEPO) technique and compare results with other strategies such as GA and swarm techniques. The comparison leads to the dominance of the MOSHEPO technique for economic load dispatch solutions. In [42], the authors employ mixed-integer linear programming for power flow management of a hybrid microgrid. A multi-objective approach to minimize the operational cost and CO_2 emissions is applied with demand-side management. The energy storage systems scheduling is carried out with a fuzzy interface.

In the light of the above-mentioned reviews, Figure 3 shows a general power flow algorithm from start to end. After the steps of initialization and application of the heuristic algorithm, if output with feasible results is obtained, the algorithm ends, else it continues to solve for the parametric values.

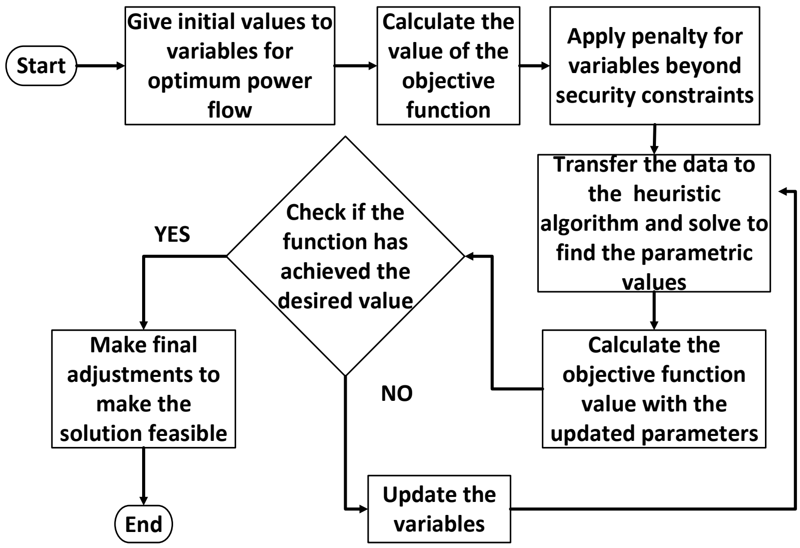

Figure 3. Power flow general algorithm.

4.2. Optimization Techniques Regarding Uncertainty

One of the major problems in a microgrid is to track the output fluctuation of the distributed generation by means of mechanical and electromagnetic regulation. The real culprit behind this problem is the volatility and randomness in renewable energy resources. The massive integration of renewable energy resources further leads to the issue of frequency offset and voltage fluctuation in a power system, lowering its quality. Although many electronic devices deal with this problem, they increase the system complexity and stability and are also limited in response speed and accuracy. Further, the cost of the objective function increases if we try to curb the uncertainties, as shown in Figure 4. The AC-DC hybrid system also allows users to participate in energy management and trading actively. The users make different decisions based on energy prices, which adds to uncertainty in energy production and consumption. The main methods employed to deal with uncertainty are stochastic programming and robust programming. As robust programming does not deal with interrelationships between uncertainties, the trend shifts in favor of stochastic programming to resolve this issue.

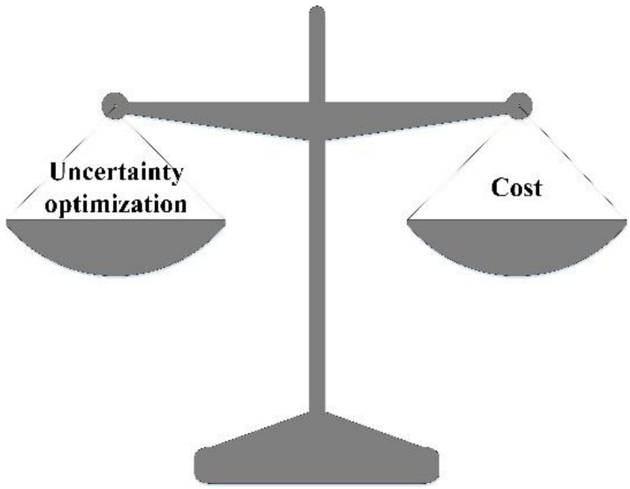

Figure 4. Relationship between uncertainty optimization and overall cost.

In [43], the authors proposed a novel framework with day-ahead scheduling based on a distributional robust optimization model and intra-day multiple time scale (MTS) rolling optimal dispatch. This DRO model is reduced using the mixed-integer linear programming (MILP) approach, employing column and constraint generation algorithm, and achieves the optimal dispatch dealing with the uncertainties. It is compared with the existing adaptive robust optimization (ARO) model and shows better performance and results, reducing the load shedding and source abandoning in a hybrid microgrid. The impact of time interval needs to be further explored in this model.

In [44], the authors presented a two-stage robust optimal dispatch model dealing with the state variables of distributed generation cost, schedule of power exchange, charging and discharging of batteries, and the power involved with interlink converters. It also employs the MILP approach to reduce the model and achieves optimal dispatch in light of uncertainties using column and constraint generation algorithm.

In [45], the authors propose a stochastic load flow model based on unscented transform and modified crow search algorithm (MCSA) for uncertainty in variables of active and reactive loads, wind and solar power generation, and market power price for the power exchange among the sources and between sources and the grid. A new two-stage crow search algorithm is applied to enhance the ability of the existing algorithm to avoid premature convergence. It shows that model based on MCSA delivers better performance, but the cost of the system is higher in order to minimize the uncertainties in the variables mentioned above. In [46], the authors compare two approaches using Petri nets and fuzzy logic to design and implement a system for the schedule of power dispatch of a real-time hybrid microgrid. The constraints of cost optimization, grid supply limitation, load demand, and power losses are taken under study. It shows that fuzzy logic manages the constraints of the hybrid microgrid in a superior manner and hails out as a better approach. A new supervision system is suggested to manage the data regarding random variables of weather, speed of the wind, solar irradiance, and temperature in remote areas for hybrid power generation. In [47], the authors suggest a stochastic model employing cloud theory based on fuzzy logic to deal with the uncertainties related to wind and solar power, load demand, and market price. A proposed modified flower pollination algorithm (MFPA) is compared with the existing optimization algorithms in light of different scenarios. MPFA employed with a stochastic model, based on cloud theory of fuzzy logic and probability, shows better optimization with minimum deviation in all scenarios comparatively.

In [48], the authors propose a stable distribution probability model and load prediction analysis to assess the uncertainties related to solar and wind generators in hybrid grids. It employs the CPLEX algorithm to solve the non-chance constrained model, converts the chance model to non-chance using stochastic simulation and neural network, and then applies chaos particle swarm optimization (CPSO) to solve it. It effectively deals with the uncertainty leading to an overall increase in the cost. In [49], the authors propose a risk-based uncertainty set optimization model, which is reduced using the MILP approach. The paper focuses on renewable power curtailment in a hybrid microgrid for an energy management system to achieve an optimal cost of operation.

In [50], the authors present a novel energy management system to accurately determine the market rates due to weather conditions, policy and demand making, errors in forecasting techniques, cost of fuels, and the linked uncertainties by employing a robust optimization technique. The simulation results of using the Monte Carlo technique show a 53.31% reduction in fluctuations. In [51], the authors employ a robust optimization approach to satisfy the energy demand, maximizing the utilization of renewable resources and minimizing the fuel-based generators. The MILP technique is used with the MATLAB *linprog* toolbox to simulate the system, showing an increase in system efficiency. In [52], the authors use an interval-partitioned un-certainty (IPU) based robust dispatch technique to close down the un-controllable renewable generators with the big M method. It employs column and constraint generation for the tri-level robust optimization and struggles to minimize the conservativeness of the results without any compromising in the system robustness. In [53], the authors employ a piecewise linearization strategy combined with the quadratic Newton–Gregory interpolating polynomial technique to tackle uncertainty in the developed risk-based optimization model of the hybrid microgrid. In [54], the authors propose a deterministic coordinated scheduling model and then apply a hybrid stochastic interval method to tackle the uncertainties in the hybrid microgrid. In [55], the authors propose a two-stage optimization process to cater to the uncertainties in generation system and consumption loads, leading to an enhanced robust power supply by system operators. Firstly, the stochastic optimization of the microgrid is carried out to reserve the regulation capacity in light of energy forecast uncertainties, followed by the rescheduling of initial planning according to signal request and economical offer from system operators.

Based on the discussion on the uncertainty modeling in the references mentioned above, the authors present the classification of uncertainty modeling in Figure 5.

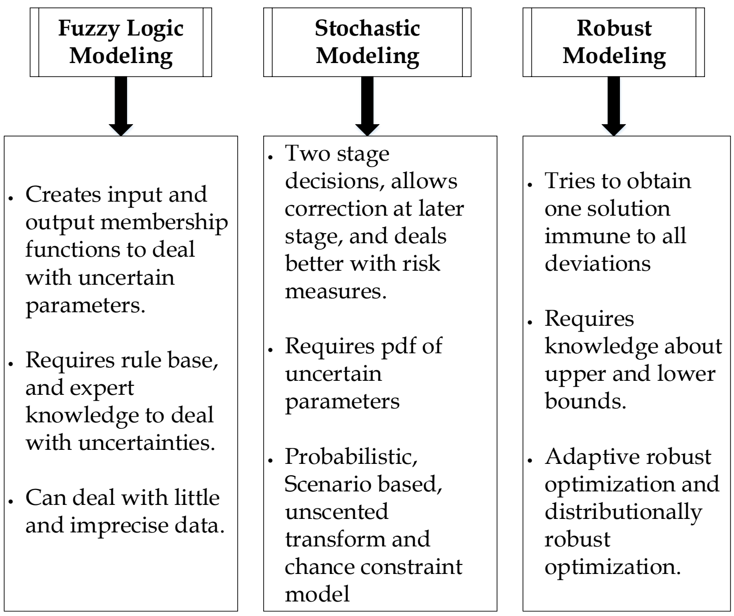

Figure 5. Classification of uncertainty modeling.

4.3. Optimization Techniques Regarding Design and Topology

The most important part of a power system is its optimal planning and configuration. The optimization of designing a power system comprises the selection of the best technique or combination of schemes from all system design and equipment parameters. It also considers the constraints of the environment, various resources, and system operation. The latest studies in this field have been summarized below.

In [56], the availability and cost of equipment at the design phase are chosen as the major constraints, and multi-objective particle swarm optimization (MOPSO) and genetic algorithm approaches are compared in light of scenarios of basic and maximum renewable energy resources integration. The results demonstrate that MOPSO has superior performance related to decreasing cost and improving availability.

In [57], the authors propose a mixed-integer coordinated model for generation and storage optimization in a hybrid microgrid. It employs the benders decomposition algorithm to find the optimal solution. It is required to incorporate the attenuation effect of these energy storage devices in the existing model. In [58], the authors work on the optimal installation of the DC feeders to minimize the cost of installed distributed energy resources, converters, distribution lines, and other economic and security constraints. The results emphasize the installation of energy resources in the same AC-DC type power network to avoid converters and save cost. The DC lines installation cost gets minimized if DC loads are connected to DC buses integrated into DC feeders. In [47], the authors use a multi-objective approach employing mixed-integer nonlinear programming and Monte-Carlo technique for the remote islanded microgrid. The results demonstrate that as the fuel cost intensifies, the microgrid will be least dependent on fuel-based units. It depends more on renewable energy, hence minimizing the converter operational cost. In [59], the optimal sizing of power in a standalone microgrid has been analyzed with the help of a modified artificial bee colony (MABC). The proposed technique enhances the usage of renewable energy in the microgrid.

In [60], the authors propose a novel two-stage algorithm for optimal sizing of a hybrid microgrid. The first stage deals with the optimal sizing, employing the metaheuristic technique, while the second stage caters to the required design problem with the help of a nonlinear solver. In [61], the authors propose a novel optimal sizing strategy by developing a stochastic model to curb the uncertainties and applying the optimal sizing objective function with respect to minimal operational cost. In [62], a mathematical model for sizing components in a hybrid microgrid is introduced which evaluates the load demand and proposes a system with minimal cost, keeping in view the uncertain nature of power from renewable sources. The model is applied in a town in Malaysia, and a feasible model is obtained with optimal cost.

In [63], the authors employ equilibrium optimization (EO) to select optimal microgrid design for the given load at minimal cost and high stability at varying climate conditions. The results show fast convergence achieved with the EO algorithm as compared to other recent metaheuristic techniques. In [64], software HOMER is employed to optimally design a hybrid micro gird that can cater to the load demand while minimizing the overall cost, fuel consumption, and carbon dioxide emissions.

Keeping in view all the references mentioned above, Table 1 incorporates a comparative analysis of all the techniques employed for each classification of optimization. It shows the latest research trends in all areas involving optimization techniques and also presents new models regarding hybrid microgrids. The majority of articles focused on developing the modified version of existing heuristic techniques to solve the concerned problem in a faster and better-formulated way. It shows the deep interest of the research community regarding power flow uncertainty optimization with stochastic modeling, fuzzy logic, and robust programming. The trend of research is shifting in favor of battery storage optimization and the integration of plug-in hybrid vehicle load in the grid.

Table 1. Optimization approach; problem, methods, and techniques applied; and recommended method.

Ref. No.	Approach		Problem			Optimization Methods and Techniques	Recommended Method/Technique
	SO	MO	PF	UC	DN		
[26]	✘	✔	✔	✘	✘	Memetic Algorithm (MA), Improved Memetic Algorithm (IMA)	IMA
[27]	✘	✔	✔	✘	✘	Multi-objective Particle Swarm Optimization (MOPSO), PID for converter, PI and Fuzzy Logic Controller (FLC) for battery charging/discharging	MOPSO for converter FLC for battery
[28]	✔	✘	✔	✘	✘	Centralized and decentralized OPF using Kriging model of power electronic transformer (PET)	A decentralized approach using PET
[29]	✔	✘	✔	✘	✘	FLC for load management	FLC
[30]	✘	✔	✔	✘	✘	FLC using MOPSO, Multi-Objective Genetic Algorithm (MOGA)	MOGA
[31]	✔	✘	✔	✘	✘	Stochastic model, solved using scenario reduction (SR) and Benders decomposition (BD)	SAME
[32]	✔	✘	✔	✘	✘	DPR using interior point method (IP)	SAME
[33]	✔	✘	✔	✘	✘	AC/DC OPF using IP, UPF algorithm	AC/DC OPF using IP
[34]	✔	✘	✔	✘	✘	Expectation programming model, chaotic particle swarm optimization algorithm (CPSO), TOU, spot price method	Spot Price Method
[35]	✘	✔	✔	✘	✘	Probabilistic model using Monte Carlo (MC) and SR	SAME
[36]	✔	✘	✔	✘	✘	Conventional ac grid, hybrid AC/DC microgrid, plug-in hybrid electric vehicles (PHEV) load optimal power flow with GAMS software	MILP
[37]	✔	✘	✔	✘	✘	Compartmentalization strategy, nanogrids solved with pinning synchronization technique for optimal power flow	SAME
[38]	✔	✘	✔	✘	✘	Sub microgrids solved with multileader and multifollower game theory-based optimization model for optimal power balance of 3 phase hybrid microgrid	SAME
[39]	✘	✔	✔	✘	✔	Use of HOMER software to reduce the cost of energy and environmental emissions from hybrid microgrid for the designated load	SAME
[40]	✘	✔	✔	✘	✔	Reducing the cost of energy and environmental emissions using Particle Swarm Optimization PSO	PSO

Table 1. *Cont.*

Ref. No.	Approach		Problem			Optimization Methods and Techniques	Recommended Method/Technique
	SO	MO	PF	UC	DN		
[41]	✘	✔	✔	✘	✘	Economic dispatch using Multi-Objective Spotted Hyena and Emperor Penguin Optimizer (MOSHEPO) technique	MOSHEPO
[42]	✘	✔	✔	✘	✘	Reducing the cost of energy and environmental emissions using mixed-integer linear programming (MILP) and FLC for battery charging/discharging	SAME
[43]	✔	✘	✔	✔	✘	Robust optimization adaptive robust optimization (ARO) and distributional robust optimization (DRO) model with (MILP) using column and constraint generation algorithm (C&CG)	DRO model
[44]	✘	✔	✘	✔	✘	Two-stage robust optimization (TSRO) using MILP and C&C, DO	TSRO
[45]	✘	✔	✔	✔	✘	A stochastic model based on unscented transform (ST), modified crow search algorithm (MCSA), crow search algorithm (CSA), particle swarm optimization (PSO), genetic algorithm (GA)	MCSA
[46]	✔	✘	✔	✔	✘	Petri Nets (PN) and FLC	FLC
[47]	✔	✘	✘	✔	✘	PSO, GA, Flower Pollination Algorithm (FPA), Modified Flower Pollination Algorithm (MFPA using FLC)	MFPA
[48]	✔	✘	✘	✔	✘	Stochastic modeling, CPLEX using neural network (NN) and CPSO	SAME
[49]	✔	✘	✘	✔	✘	Symmetric (ASREM) and asymmetric (ARREM) robust energy management techniques	ARREM
[50]	✔	✘	✔	✔	✘	Robust optimization with Taguchi's Orthogonal Array method	SAME
[51]	✔	✘	✔	✔	✘	Robust optimal power management system (ROPMS) with MILP	SAME
[52]	✔	✘	✔	✔	✘	Single interval (SI), partition interval (PI) robust optimization with C&CG algorithm	PI robust optimization
[53]	✔	✘	✘	✔	✘	Piecewise linearization with Quadratic Newton Gregory interpolating technique for variable linearization, and Chebyshev consistent linear approximation for converter efficiency, solved with MILP to counter uncertainties	SAME
[54]	✔	✘	✘	✔	✘	Coordinated scheduling with hybrid stochastic interval method to counter uncertainties	SAME
[56]	✔	✘	✘	✘	✔	Availability and cost of equipment using MOPSO and MOGA	MOPSO
[57]	✘	✔	✘	✘	✔	Generation and storage optimization using mixed-integer coordinated model and BD	SAME

Table 1. *Cont.*

Ref. No.	Approach		Problem			Optimization Methods and Techniques	Recommended Method/Technique
	SO	MO	PF	UC	DN		
[58]	✔	✘	✘	✘	✔	New design model for dc feeder placement	SAME
[59]	✘	✔	✔	✘	✔	Modified Artificial Bee Colony (MABC)	MABC
[60]	✔	✘	✘	✘	✔	A two-stage approach where first genetic optimization-based technique is applied followed by nonlinear solve for optimal sizing	SAME
[61]	✔	✘	✘	✔	✔	Obtaining pdf of wind and PV power and using an objective function to minimize cost	SAME
[62]	✔	✘	✘	✔	✔	Stochastic swarm optimization-based regression for optimal sizing with minimal cost	SAME

Abbreviations: SO—Single Objective, MO—Multi-objective, PF—Power Flow Optimization, UC—Uncertainty Optimization, DN—Design Optimization, SR—Scenario Reduction.

5. Hybrid AC/DC Microgrid Control Strategies

The hybrid ac/dc microgrids have many benefits, but they require very complex control methodologies for operation as they integrate the AC and DC subgrids. The integration control is a hub of modern control research, and nonlinear control techniques and other novel approaches are underway to integrate hybrid microgrids efficiently. The hybrid AC/DC micro grids involve more complex control strategies for power management and control compared to AC or DC micro grids due to their reliance on the ICs controls [65]. This section focuses on the strategies that can be employed for power management in hybrid microgrids, highlights the trending research areas, and identifies the specified paths for future research.

5.1. Power-Sharing Control

Adjustable speed drives, power supplies, and wielding machines, and many more are categorized as nonlinear loads. When the AC bus is loaded with nonlinear load, a highly distorted current enters the power system, which is usually called harmonic current. Practically, it is difficult to extract harmonics from load current directly since microgrid is very widely distributed with these types of loads [66]. In [67], the authors propose a unified control of the autonomous operation of hybrid AC/DC microgrid where slack terminal in AC/ DC microgrid enables power-sharing between ICs through autonomous control, keeping in view distributing total demand among AC and DC slack terminals proportionally. In [68,69], the authors suggest a remedy to this issue and offer a method to get interlinking converter harmonic current reference through its terminal voltage. A first-order high pass filter with a cut-off frequency of 15 rad/s is used to reduce harmonic. The voltage on AC bus common coupling point (PCC) is kept sinusoidal even in the presence of nonlinear load by converter with the injection of harmonic current. A resonant and repetitive controller is used for implementation which offers higher stability of the system. Each power converter operates independently having no communication link between them, so this is implemented easily and at a reduced cost.

Many topologies of hybrid microgrids regarding conventional droop control have been employed where mostly the intermittent distributed generators operating on maximum power point tracking are employed in the scenario of power-sharing and control. A droop-based control strategy was designed with enhanced power-sharing for hybrid DC/AC microgrids. The opportunity is present to interconnect DC microgrid and AC microgrid through an interlinking converter to form a hybrid microgrid when DC and AC microgrids are available in distribution generators. Adequate frequency/voltage control and power-sharing are the essential functions of DC and AC Microgrid control systems in a standalone mode. Active power-sharing in the entire system has to be accurately attained by regulating the interlinking converter's active power input when it comes to a hybrid microgrid. Moreover, when the interlinking converter participates in a reactive power of AC microgrid, it adds some more complexity to a hybrid microgrid control system. The existing droop controller utilizes frequency deviation to calculate the reference active power for interlinking converters, and it is usually a current-controlled converter. This method has a limitation in that it only focuses on power-sharing, neglecting small frequency deviations due to which the system presents poor power quality (no support to AC subgrid and bus voltage) and stability issues; hence, it is required to have some reference for detection other than frequency [69–73].

In [74], the authors employ secondary voltage control, in which each distributed generator requires only its own information and that of some neighbors, to improve the system reliability. In [75], the authors discussed a decentralized power management system that considered multiple subgrids and common bus topology of hybrid microgrids and made coordination among different subgrids. The conventional droop control is utilized that focuses on AC frequency and DC voltage whose main purpose is to equally distribute all fluctuations in all subgrids as per their power ratings. It also considered islanded mode of operation that is supported by incorporating a storage subgrid that is responsible for maintaining common DC bus voltage for power balancing in islanded mode. In [76], the authors incorporate the parallel operation of a hybrid microgrid by bidirectional converters (BDC), which are responsible for power transfer from DC to AC side of hybrid microgrid and vice versa. However, as they are power electronic converters, they are operated by operating a switch at a specific frequency due to asynchronous switching of the parallel-connected converter. A circulating current flows among multiple converters which tend to lower the power rating of equipment and can cause power-sharing deviation mainly in island mode. A unified detection method of circulating current is suggested to address this issue, e.g., virtual impedance controller in combination with droop controller to solve circulating current and power-sharing problems simultaneously.

In [77], the authors propose an active power-sharing and control strategy by utilizing a synchronization machine (VSM) responsible for the inertial improvement of AC bus frequency and DC bus voltage of a hybrid microgrid. The VSM works by observing rotor dynamics of a synchronous generator, the virtual inertia, and damping control of AC bus frequency and DC bus voltage simultaneously. This damping indicates the variation of transferred power, therefore, to restore frequency and voltage at its original values. This control technique has the advantage of operation in both grid-connected and islanded modes of operation. It is quite evident that when an abrupt change or fluctuation appears in a hybrid microgrid, AC bus frequency and DC bus voltage can easily damage, which in turn severely affects power system quality. To deal with such issues, in [78], the authors proposed adjustable inertia on ICs to improve the dynamic performance of a hybrid microgrid. The proposed control method helps in improving inertia support for both AC and DC buses and protects ICs from conversion failures in a state of transition. This technique deploys an arctangent function to limit capacitor voltage so that in case of power fluctuation, it may not lower the minimum conversion voltage, and it seems to work well with the systems that utilize batteries in the dc subgrids. Similarly, in [79], the idea is based on partially decoupling the inductor current dynamics by introducing a constant virtual resistance with bounded controllable voltage for ICs, power rectifiers, and boost converters. In all these cases, the dynamics of virtual voltages guarantee desired upper bound for converter current regardless of the direction of power flow by introducing a constant virtual resistance with a bounded dynamic virtual voltage for all converters. Results show that input current follows maximum required values, ensuring exceptional power-sharing, voltage regulation, and input current limitation.

In [80], the authors propose the autonomous operation of interconnected converters could also be achieved but taking into account the failure of tracking droop variation in droop control parameters, a centralized controller. It can be deduced from the comparative analysis that centralized control offers optimized power exchange and works identically during the parallel operation of converters. Many researchers proposed decentralized load sharing and power management methods for hybrid microgrids, considering the operation of photovoltaic and battery units.

In [81], the authors employed a modified droop control method to control photovoltaic power, while in [82], the authors considered real-time control with both energy storage and pulsed loads. Due to intermittent generation, grid isolated systems require special attention. A comprehensive frequency scheme and active power decoupling method are used to link the AC and DC buses while simultaneously regulating the voltage and frequency of the grid. The power flow among AC and DC subgrids can be well managed by interlinking converters, and these are interconnected with the conventional DC voltage-based droop approach. This approach may cause overstressing of converters due to the line resistance effect, so employing multiple converters for AC/DC subgrids seems a viable option. In [83] and [84], the authors proposed superimposed frequency and decentralized coordination methods, respectively, in the DC subgrid. In [84], the authors coordinate the DC sources and interlinking converters by the injected ripple frequency; however, the introduction of a global variable enables accurate sharing of the power of converters as per their rating. This method attains load sharing without any effect on online resistances. It also manages power-sharing among AC and DC subgrids with benefits of no circulating current, proportional power-sharing, DC link regulation, and maximum power transfer. In the presented technique, the only information that a converter requires is about the status of its neighbor.

In [85], the authors suggested localized distributed controllers, which generate power references for each interlinking converter. Using this technique, each converter is allowed to exchange information in distributed communication, hence sharing power as per their own rating. Energy storage subgrid systems are very special in microgrids as they can maintain regulated voltage in case of islanding operation considering this requirement.

In [86], the authors discussed the implementation of an AC dynamic local voltage compensator which is dependent on the distributed energy storage system and is responsible for active power-sharing in case of the regulatory requirement. Moreover, they utilize a voltage-controlled method that does not require frequency measurements. It shows the capability of the direct control of AC voltage with better voltage quality.

In [87], the authors propose synchronverter technology that uses a controlled converter to maintain active power-sharing and power quality. The direct frequency control method is utilized in which DC-side voltage is measured and gets real-time reference frequency corresponding to the DC-side voltage variation. Then frequency is sent to a low-pass filter (LPF) to avoid high-frequency harmonics resulting in the fluctuation of frequency and active power. It aims to realize active power-sharing and improves the transient frequency stability fluctuation of frequency and active power.

Model predictive methods involving predictive current and power (MPCP) and model predictive voltage and MPVP scheme are gaining attention among researchers to realize different operational modes, e.g., power generation, fluctuations, power demand, battery state of charge, and efficient energy management system. One disadvantage of the discussed method is that in comparison to other conventional controllers, these model predictive controllers need additional sensors and measurements. Hence, they require not only extra communication facilities but also high cost. Moreover, in practice, modeling such a big microgrid is a tidy task that can always offer some errors, which are yet to be further addressed in future work [88].

Reference [89] suggests series-connected converters with static VAR compensator for hybrid AC and LV DC microgrids. The authors presented P-δ and Q-P-V droop control for both converter and SVC parts, presenting the phase angle of the voltage of fundamental reactive power and fundamental droop control voltage. The proposed converter also suppresses harmonic components by determining SVC impedance which in turn has two thyristors that are triggered in every half cycle. The authors did not discuss anything about stability and circulating current problems.

In ICs containing bidirectional converters, as power flow between AC and DC subgrid and its direction changes, it largely degrades the system's stability. Reference [90] investigates the effect of power flow on the small-signal stability of hybrid microgrid by using a linearized state-space model and its eigenvalue analysis. Moreover, sensitivity analysis is also performed to study stability margins. It is concluded that power flow from DC to AC sub-grid is more stable than AC to DC sub-grid.

Secondary control strategies are conventionally studied independently for each side of a hybrid microgrid, neglecting the interaction of AC and DC sides, which cannot completely analyze dynamic response and power-sharing. Reference [91] presents a novel distributed secondary control strategy for a hybrid microgrid that regulates AC/DC voltage magnitude and frequency by employing distributed consensus approach. This method not only improves power-sharing and control but also avoids circulating current due to multiple ICs.

When switching from islanding to grid-connected mode, different frequency, phase angle, and amplitude may impact and sometimes even collapse, so there is a need to smoothen the process of switching from island to grid. Reference [92] proposes a design of pre-synchronization control of amplitude and frequency, which is based on droop control and disturbance observation that quickly tracks the sudden change of system current and suppresses the difference of tracking and actual value so as to generate smooth switching effectively.

Relevant to the above discussion, Table 2 shows the different control techniques implemented in different research articles. It shows the research community's interest in favor of droop control and that new research is taking place in model predictive control giving promising results. In an islanded mode of operation of a microgrid, to regulate frequency and voltage, control strategies are proposed and are summarized in Table 2. The most commonly used one is droop control, whose main purpose is to stabilize frequency in case of any mismatch between generation and demand. The P-F and Q-V droop methods are usually used to allow flexibility as real power demand increases output frequency reduces. Reactive power also follows the same case, i.e., output voltage magnitude decreases with an increase in reactive power demand. Conventional droop control offers many limitations, e.g., poor power-sharing, no harmonic current sharing in nonlinear loads, and low voltage regulation. Due to these problems, many variants of droop control such as voltage-real power and frequency reactive power droop, angle droop, adaptive droop, and virtual impedance methods are proposed. The virtual impedance approach adjusts the output voltage by adjusting the virtual impedance. Still, in the case of nonlinear loads, this technique offers very high total harmonic distortion, so a high pass filter needs to be used. The virtual inertia approach is also a modified form of droop control. The main purpose of this technique is that in case of maloperations of frequency relay, it avoids unwanted operation of circuit breakers.

Figure 6 presents the control strategy and converters used with their controlling variables.

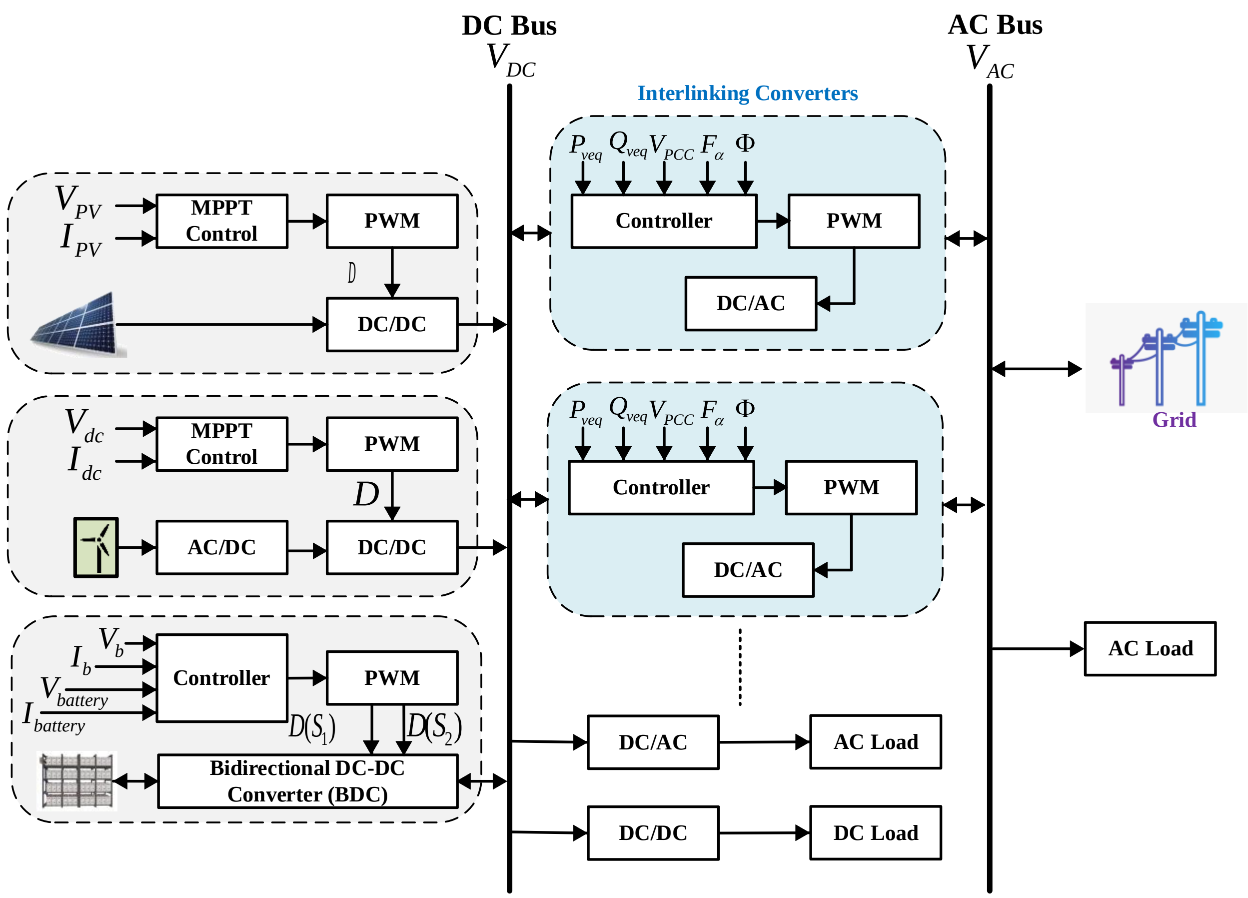

Figure 6. Control of AC/DC hybrid microgrid [23].

Table 2. Majorly discussed control techniques in power-sharing control.

Sr. No.	Method	References
1	Conventional/modified droop control	[68,70–73,75–83,85–88]
2	Virtual impedance control	[76,81,85,86]
3	Model predictive control	[88]
4	Virtual inertia control	[69,82,87]

5.2. Power Generation Control

In [93], the authors achieve optimized transient performance in hybrid DC/AC microgrids by an improved virtual synchronous generator (VSG) for its high-performance control strategy. This improved control strategy is achieved by modifying a standard virtual synchronous generator. An additional controller is embedded in an improved virtual synchronous generator to use in grid-connection, which is pre-synchronized. To analyze the stability of a system, a small-signal model for an improved virtual synchronous generator is also built. The power output of the hybrid DC/AC microgrid is assisted by another controller, which is built for the energy storage system. Various transient cases of conventional virtual synchronous generator control, droop control, and the improved virtual synchronous generator were tested under all possible conditions. The pre-synchronized controller is also tested. The results of the tests show that the performance of the improved virtual synchronous generator is smoother than the conventional virtual synchronous generator. Randomness and uncertainties in distributed generations cause an effect on permeability. Due to vulnerability and uncontrollability to interference, the conventional power transformers in the architecture of smart micro are not suitable in smart buildings [94].

To segregate the obstruction to the grid and to enhance the saturation of distributed generation, hybrid microgrid architecture for a smart building is present. Thus, in a complicated and changing grid environment, the stability and the safety of a system can be ensured. This architecture got the following advantages. (1) Modular multilevel converter-based solid-state transformer (MMC-SST) is fully used for controllability. (2) The complementary space of distributed generations and the time characteristics. (3) The energy storage systems have the peak shaving capacity. The typical operating mode characteristics were analyzed, i.e., off-grid mode and grid-connected mode. The complete control strategy merging with the features of each mode is aimed. After all, the complete control strategy and the efficiency of the architecture are tested through a simulation. For the effective utilization of distributed renewable energies, a microgrid is an efficient method. Due to the high perforation of distributed renewable energies, consuming and coordinating a huge quantity of distributed generators within alone microgrid has become infeasible, which causes a continuing transformation in distribution systems [95]. The forming of a microgrid cluster by interlinking multiple microgrids is an effective way to enhance the quality of operation for the larger-scale integration of distributed generators.

To form the microgrid clusters, the control coordinated operation and the flexible configuration between multiple microgrids have not been sufficiently referred to. The solution to this problem is a novel design of architecture for numerous microgrids and their coordinated control schemes. In a first step hybrid unit of common coupling is designed, which is an advanced microgrid interface and used in place of the traditional point of common coupling. The hybrid unit of common coupling utilizes a modular multilevel converter as its main module and delivers DC and AC interfaces mutually. The hybrid unit of common coupling based is developed for multiple microgrids, where these microgrids were interconnected via the DC interface and were grid-connected via the AC interface.

The coordinated control schemes beneath various operation circumstances are built on the suggested architecture. The hybrid unit of common coupling-based architecture was tested in PSCAD based on the demonstration project in Guangxi, China. The results of the simulation of interconnected microgrids with a suggested architecture and control schemes show that it works efficiently and effectively under various scenarios. The suggested control scheme and architecture is not only optimizing the use of distributed generators but also improve the large-scale incorporation of distributed renewable energies.

A decentralized control strategy is proposed for a hybrid microgrid that regulates the voltage magnitude of a joint DC/AC bus in every single microgrid. For this purpose, new droop characteristics for resources across mutually interlinking converter and Microgrid were proposed. The better voltage regulation is achieved along with a better reactive/active power-sharing across both microgrids by the proposed droop model. The simulation shows the improvement in the result [96].

A model-based controller was designed for a bi-directional interlink converter in a DC sub-grid of a hybrid microgrid, which regulates the output voltage. A step response was applied in the interlink converter to construct a linear time-invariant system indicating the DC subgrid. A controller based on the model of interlink converter was developed using a closed-loop system, which is formed on the basis of a PID controller and an LTI model obtained [97]. In [98], the authors propose the control of a hybrid AC/DC microgrid under both parameters. Load alteration is achieved by a robust control technique working on the principle of sliding mode surface. A uniform control strategy was designed for a bidirectional DC/AC interlinking converter in a microgrid. The different control structures were designed for a multifunctional bidirectional DC/AC interlinking converter in terms of DC and AC voltage support and power management by an unvarying control strategy [99].

With this combined control structure, several trigging mechanisms for bidirectional DC/AC interlinking converter mode-switch are not obligatory in reaction to a significant situation variation in a power network. Thus, the adverse effects, i.e., system collapse and unsmooth transition due to a slower mode switch can be avoided. Furthermore, the hierarchically controlled hybrid microgrid is applied by a uniform control strategy, and decentralized and centralized levels are compromised by control architecture. This affects the transmission failures, and thus, transmission error ride-through capability will be lessened.

A power flow analysis method was designed for a hybrid microgrid system, and on the other hand, a steady-state model was designed for a multi-port electric energy router. The purpose of both methods is to consider the control strategies. In the first step, DC and AC port equivalent components along with a circuit topology model of electric energy router are set ahead. In the second step, considering the outer control characteristics of an electric energy router, control strategies involving droop mode, PQ mode, and V/f mode are formed which were appropriate for system testing. In the end, a model of AC/DC power flow was formed by applying the extended sub-network model [100]. The expanded AC/DC network modification equations and the AC/DC network admittance matrix were used to resolve the challenge with regard to the power flow procedure for hybrid microgrid systems. Electric energy routers could be used for voltage improvement and flexible power regulation, which is explained by two examples. Moreover, the power flow analysis method of a hybrid DC/AC Microgrid is proven to be efficient.

In [101], the authors propose conventional power generation and consumption with the high perforation of renewable energy resources. It is a challenging task to integrate these microgrids with the distribution networks. A coordinated control strategy is designed for a microgrid with DC/AC loads and hybrid energy resources. Initially, for a distributed converter, a local-level coordinated control strategy is designed. A method based on model predictive voltage and power control is designed for DC/AC interlinking converters to make sure smooth power transfer among DC and AC subgrids and to deliver high-quality voltages. Meanwhile, efficient grid connection and synchronization can be attained. Finally, an energy management scheme at a system level is implemented to confirm balanced operation beneath consumption conditions and variable power generation. The effectiveness of a recommended control strategy is demonstrated on a 3.5 MW system. The perforation of Renewable Energy Resources, i.e., wind energy systems and photovoltaic systems, is gradually expanding into traditional power systems. On the other hand, there is a drawback of losses in AC-DC-AC conversion in renewable energy resources, drop-in power quality, and increase in the cost of components [102].

Furthermore, in recent times, the demand for power of DC load, i.e., electric vehicles and telecom exchange network systems, is increasing. For the telecom network systems, the DC loads were associated with the main AC grids under some converter phenomena in traditional power systems, which cause the enhanced cost and occurrence of AC to DC conversion losses. The appropriate solution to lessen the numerous reversal conversions inside the telecom exchange is a hybrid microgrid for the dispersed DC and AC power generations. Therefore, a droop-controlled scheme was used among DC and AC microgrids for the hybrid microgrid for energy management and managed power and voltage regulation inside a telecom exchange. The required power is shared among DC and AC microgrid by the droop controller and improves operational consistency of the DC loads, such as electric vehicles and telecom exchanges. For the betterment of interlinking of various distributed generation systems in the microgrid and manipulating the major characteristics of both DC and AC microgrid, an improved hybrid microgrid was designed. For the connection of these microgrids, an interlinking DC/AC converter is required with a control strategy and proper power management. The interlinking converter was planned to work as a load at one microgrid and at the same time work as a supplier to the second microgrid, and the power management system is responsible for the power-sharing in both DC and AC sources of a microgrid during an islanding operation. There are management issues and power flow control problems between different sources distributed over both DC and AC microgrids. A decentralized sharing of power method is designed to reduce the necessary communication among microgrid and distributed generation systems. The efficiency of a system enhances and the cost decreases by allowing different DC or AC sources and loads to be submissively placed in order to reduce the demanded power conversion stages in a hybrid microgrid. The performance of the presented system is tested on the simulation in PSCAD/EMTDC software [103].

Under islanding operation conditions, a control method was designed for the hybrid microgrid. Several control schemes for DC subgrids and AC subgrids were examined. According to the operational reliability and the requirement of power-sharing, an additional key control scheme is designed for interlinking a converter with energy storage or DC-link capacitor, which will dedicate to the appropriate power distribution between DC and AC subgrids to sustain DC and AC side voltage balanced. The developed control methods specified for the DC and AC subgrids were combined with an interlinking converter. The power flow shifted between subgrids to enhance the efficiency and operating quality can be managed by interlinking converters [104].

A new energy management technique is designed for hybrid DC/AC microgrids in the field of remote communication. The minimization of regular operation costs while providing purified water to the remote communities, sustaining practical functioning parameters of microgrids, and meeting the consumer preferences is the major goal to achieve by the new energy management technique. This goal is achieved by performing the real-time supervisory control on all present controllers of a system in both demand and generation sides. On the demand side, to attain the lowest operational cost and to satisfy consumers' requirements for the water purification units and domestic appliances, an optimal operational schedule was developed, while on the generation side, conventional and renewable generation units were integrated to make a distributed system. Droop parameters were used to satisfy the demand in conventional distributed generators, while the maximum power point tracking algorithm was used in renewable sources of energy to increase the efficiency of a system. Furthermore, the bidirectional power flow allowed by DC/AC interlinking converters for both DC and AC sections of a microgrid is also controlled by a new energy management technique [105].

An adaptive rolling-time horizon is utilized by the proposed energy management technique in response to disturbances/changes in user input or by the system in a practical real-time operation. Mixed-integer nonlinear programming modeled the assets scheduling problems. The effectiveness of the new energy management technique is tested on a hybrid AC/DC microgrid in a simulation. The purpose of delivering an anticipated power-sharing and uniform DC-link voltage for a distributed energy storage system is built on the base of a hybrid microgrid during load changes. A zero dynamics-based mathematical equation for all the converters used in a system-based controller was designed, which controls a grid-connected DC/AC converter, lithium battery-based storage system, and PV system [106].

A bidirectional buck-boost converter was used in a distributed energy storage system, and two buck converter photovoltaic system, supply, and a grid power quality of grid-connected loads were enhanced by a grid-connected converter and also responsible for the damping of the DC-link voltage variation. Moreover, in dynamic and steady-state conditions, a proposed model is delivering accurate coordinates. The system is tested on different operating conditions, and the results were satisfactory. All over the world, most of the rural areas are isolated from the urban areas and the absence of electricity affects the development of the areas. It is due to the accessibility, less generation capacity, and affordability of the electric power in that area. A user-friendly power supply is designed to overcome that long-standing problem which generates power from renewable power generation systems using microgrid topology. For isolated rural areas' power supply, a wind augmented, cogeneration solar photovoltaic-based power generation scheme is designed. The designed hybrid microgrid provides uninterrupted electricity to the village at a very low cost. As the nature of wind and solar is not consistent, a coordinated control mechanism is also present that confirms automatically exchange of the power facility within the microgrid efficiently [107,108].

Table 3 shows the different control strategies regarding power generation in hybrid microgrids. It shows that modern research is focused on interlinking converters and droop control mechanisms, but model predictive control has recently been employed and has shown promising results in this field. Using the tuned values of PID gains fetched from optimization and the model-based controller results of the modified model show improved results. Passivity theory is used to make converge the dynamics of state variables to zero by contemplating the inserted impedance and resistance for b-q components; currents of converters and DC/DC converter were used, respectively. Error dynamics were used by the designed sliding mode surface to deliver more efficient progress for the state variables based on converters under the variations of parameters. The robustness effects of embedded sliding mode controller, the relationship among the sliding coefficients attained from the permutation of ultimate control strategy, and proposed error dynamics and the errors in the state variable of the converter were examined, and with the help of these relationships, numerous analytical curves were designed. The robustness abilities and dynamics of proposed systems were verified by hybrid microgrid parameter and load variations.

Table 4 depicts different aspects and techniques utilized to control AC/DC microgrid power-sharing. A simple subgrid consists of AC and DC bus bars to interchange power from one bus to another. The system needs to utilize some converters called interconnecting converters to increase system reliability, stability, and increased power rating. Multiple interlinking converters are used, as different vendors may have different types of subgrids; some got only renewable resources; some may have some energy storage capabilities; some may allow only linear loads while others allow nonlinear loads. Therefore, their integration with one another is another key factor. Microgrids contain a high amount of power electronics converters that may inject unwanted high-frequency components called harmonics which not only change the shape of voltage and current but also have a severe effect on efficiency, equipment life, and overall system losses, thus creating power quality issues.

Table 3. Discussion of different aspects in the literature review of generation control.

Reference	[93]	[94]	[95]	[96]	[97]	[98]	[99]	[100]	[101]	[102]	[103]	[104]	[105]	[106]	[107]
Control Strategy	✔	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✔	✘	✔	✔
Transient Response	✔	✘	✘	✘	✘	✔	✔	✘	✘	✔	✘	✔	✔	✔	✔
Grid Connection	✔	✘	✔	✘	✘	✘	✘	✔	✔	✘	✘	✘	✘	✘	✘
Controller	✔	✔	✘	✔	✔	✔	✔	✔	✘	✘	✔	✔	✔	✔	✘
Droop Control	✔	✘	✘	✔	✘	✘	✔	✘	✘	✔	✘	✘	✔	✔	✔
Permeability	✘	✔	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘
Architecture	✘	✔	✔	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✔	✘
Interlinking Converter	✘	✘	✔	✔	✔	✔	✔	✘	✘	✔	✔	✔	✔	✔	✔
Model Predictive Control	✘	✘	✘	✘	✘	✘	✘	✘	✔	✘	✘	✘	✘	✘	✘
AC/DC Conversion Losses	✘	✘	✔	✘	✘	✔	✘	✘	✔	✔	✘	✘	✘	✘	✘
Distributive Systems	✘	✔	✔	✘	✔	✘	✔	✔	✘	✔	✔	✘	✔	✘	✔

Table 4. Problems and their solution in power generation and sharing control.

Reference	Problem	Proposed Solution Strategy
[93]	Bad transient performance	A control strategy based on improved virtual synchronous generator (VSG)
[94]	Affected permeability of distributed generations (Distributed generators)	Architecture based on the controllability of the modular multilevel converter based solid-state transformer (MMC-SST)
[95]	Consuming and coordinating a huge quantity of distributed generators within the alone microgrid	A novel design of architecture for numerous microgrids and its coordinated control schemes
[96]	When interlinking converter participate in a reactive power of AC microgrid, it adds some more complexity to a hybrid microgrid control system	A droop based decentralized control strategy
[97]	Deregulation of output voltage	A model-based controller for a bi-directional interlink converter in DC sub-grid of a hybrid DC/AC microgrid based on PID and LTI model
[98]	Uncontrollability of a hybrid AC/DC microgrid under both parameters and load alteration	By a robust control technique working on the principle of sliding mode surface
[99]	System collapse and unsmooth transition due to a slower mode switch or an inaccuracy	A uniform control strategy for a bidirectional DC/AC interlinking converter in a hybrid-controlled DC/AC microgrid
[100]	The challenge with regard to power flow procedure for a hybrid DC/AC microgrid systems	A power flow analysis method for a hybrid DC/AC microgrid system and a steady-state model for a multi-port electric energy router
[101]	Challenge to integrate conventional power generators and renewable energy resources with distributed networks	A coordinated control strategy is designed for a microgrid with DC/AC loads and hybrid energy resources
[102]	A drawback of losses in AC-DC-AC conversion in renewable energy resources and drop in a power quality	A droop-controlled scheme was used among DC and AC microgrid for the hybrid DC/AC microgrid for energy management and managed a power and voltage regulation
[103]	Management issues and power flow control between different sources distributed over both DC and AC microgrid	A decentralized sharing of the power method
[104]	Operational reliability and the requirement of power-sharing and the appropriate power distribution between DC and AC subgrids to sustain DC and AC side voltage balanced	A control scheme for the interlinking of a converter with energy storage or DC-link capacitor

Table 4. *Cont.*

Reference	Problem	Proposed Solution Strategy
[105]	High operation costs while providing purified water to the remote communities, sustaining practical functioning parameters of microgrid, and meeting consumer preferences	Real-time supervisory control on all present controllers of a system in both demand and generation sides
[106]	Delivering an anticipated power-sharing and uniform dc-link voltage for a distributed energy storage system during load changes	Zero dynamics-based mathematical equation for all the converters used in a system-based controller
[107]	Absence of electricity in remote areas	A user-friendly power supply, which generates power from renewable power generation systems using microgrid topology

6. Comparison with Recently Conducted Reviews

In recent times, different reviews treating various aspects of hybrid microgrids are presented. For example, reference [109] presents a detailed review of uncertainties (only) associated with renewable energy resources-incorporated hybrid AC/DC microgrids to guarantee their optimal operation. In [110], major challenges faced in developing AC/DC microgrids built purposely to ensure a sustainable electricity system were exploited. Reference [111] presents merely a review of well-established different mathematical optimization techniques applied to one of the complex processes of microgrid, i.e., planning. Similarly, in reference [112], a review of optimization techniques, majorly the metaheuristics including ant colony optimization (ACO), GA, PSO, simulated annealing (SA), differential evolution (DE), and so on is described for microgrids embedded with hybrid energy systems (HES) to ensure economical and reliable dispatch of the resources. In [113], a comprehensive review of power management techniques of hybrid energy systems in microgrids is presented. A review of different forms (variants) [114] and hybrid forms [115] of PSO was presented to figure out the economic dispatch problems. Reference [116] provides a review of the techniques, issues, and future directions regarding the protection of distributed generation hybrid AC/DC microgrids. In [117], a comprehensive review of distributed control methods for isolated microgrids is presented. All the protocols such as linear, heterogeneous, and finite-time consensus involved in cooperative control are detailed comprehensively. As can be observed, these review papers cover one of the key parameters associated with microgrids at a time.

Table 5 presents a comparison of this review paper with other recent surveys regarding the hybrid microgrid. It shows that this paper encompasses all the major research areas regarding hybrid microgrids, discusses the relevant studies, and promotes future research directions. It also helps to identify the trending research areas where novel research has recently picked up the pace. The protection issues regarding hybrid microgrid, the strategies regarding integration of microgrids with help of interlinking converters and robust uncertainty optimization techniques, design techniques, nonlinear load handling, and droop control mechanism are the popular research areas regarding the hybrid microgrids, established by this table with the help of comparison with other surveys.

Table 5. Taxonomy of challenges, optimization strategies, and control methodologies of a hybrid microgrid.

Hybrid AC/DC Microgrid Aspects	Topic Covered	Paper Reference No.												
		[7]	[8]	[9]	[20]	[21]	[22]	[108]	[109]	[110]	[111]	[112]	[113]	This Paper
Challenges in the integration of hybrid AC/DC microgrid	Operational challenges	✔	✘	✔	✔	✘	✘	✔	✘	✘	✘	✔	✔	✔
	Power quality challenges	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✔	✔	✔
	Communication issues	✘	✘	✘	✘	✔	✔	✘	✘	✘	✘	✘	✔	✔
Optimization techniques regarding hybrid AC/DC microgrid	Power flow optimization	✘	✘	✘	✘	✘	✘	✘	✔	✔	✔	✔	✔	✔
	Battery charging/discharging optimization	✘	✘	✘	✘	✘	✘	✘	✔	✔	✔	✔	✔	✔
	PF with PHEV load	✔	✘	✘	✘	✘	✘	✔	✘	✘	✘	✘	✘	✔
	UC using stochastic programming	✔	✘	✘	✘	✘	✘	✔	✔	✘	✔	✘	✘	✔
	UC using fuzzy logic control	✘	✘	✘	✘	✘	✘	✘	✔	✔	✘	✘	✘	✔
	UC using robust programming	✘	✘	✘	✘	✘	✘	✘	✔	✘	✘	✘	✘	✔
	DN using DC feeder's installation location	✘	✘	✘	✘	✘	✘	✘	✘	✘	✔	✘	✘	✔
	DN using generation and storage of power	✘	✘	✘	✘	✘	✘	✘	✘	✔	✔	✔	✘	✔
Power-sharing and generation control	Multiple ICs	✘	✘	✘	✘	✘	✔	✘	✘	✘	✘	✔	✔	✔
	Multiple subgrids	✘	✔	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✔
	Island operation	✘	✔	✘	✘	✔	✔	✘	✘	✘	✘	✘	✘	✔
	Storage element	✘	✘	✘	✘	✘	✔	✘	✘	✘	✘	✔	✘	✔
	Circulating current	✘	✘	✘	✘	✘	✔	✘	✘	✘	✘	✘	✘	✔

7. Conclusions

The paper presents a brief overview of different aspects of a hybrid microgrid, i.e., its optimization and control topologies and challenges encountered in this regard. The hybrid microgrid is the next step in the realization of a decentralized power system and smart grid paradigm. It possesses many advantages over traditional power networks due to its improved reliability, removal of multiple conversions, and ancillary service.

In this paper, different challenges faced regarding the integration of hybrid microgrids such as operational, coordination control, regulation, lack of standards, and market awareness are discussed, and possible solutions are presented. The non-linear control of interlinking converter is of utmost significance and holds the major attention of researchers regarding the integration of microgrids. The protection of hybrid microgrids presents a major research gap, and novel techniques compromising the power quality need to be further explored in this area.

In optimization techniques, the power flow mechanism has been the beacon of research. In power flow optimization, updated models employing improved heuristic techniques have been used to ensure optimum power flow and reduce operational costs. The uncertainties regarding the DC generators were handled using stochastic, fuzzy logic, and robust techniques. The robust techniques have been found to be comparatively more cost-effective and efficient in this field. The planning and design of the hybrid AC/DC are of utmost significance and represent the first step towards the operational optimization of the hybrid grid. Over the past few years, the research pace regarding the design and topology of the hybrid microgrid has been slow and steady, and this area highlights a great need for further research. The development of new equipment, modeling of existing equipment, and application of improved heuristic techniques for optimal planning of storage and generators are important aspects of this area. It is further required to keep in view the high integration of DC generates, non-linear loads, and plugin hybrid vehicles in the hybrid grid system to optimize the system for future needs. The droop control methods have been widely explored regarding the control strategies in power generation and sharing in hybrid microgrids. Recently the trend is also shifting towards improved droop control strategies and non-linear control strategies involving model predictive control.

The power management schemes and the control strategies are immensely important in hybrid microgrid operation, demanding a comprehensive review of different microgrids operating under variable scenarios. It also presents recommendations about future specified directions of research in this field.

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