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DC Microgrid Planning, Operation, and Control: A Comprehensive Review

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ABSTRACT In recent years, due to the wide utilization of direct current (DC) power sources, such as solar photovoltaic (PV), fuel cells, different DC loads, high-level integration of different energy storage systems such as batteries, supercapacitors, DC microgrids have been gaining more importance. Furthermore, unlike conventional AC systems, DC microgrids do not have issues such as synchronization, harmonics, reactive power control, and frequency control. However, the incorporation of different distributed generators, such as PV, wind, fuel cell, loads, and energy storage devices in the common DC bus complicates the control of DC bus voltage as well as the power-sharing. In order to ensure the secure and safe operation of DC microgrids, different control techniques, such as centralized, decentralized, distributed, multilevel, and hierarchical control, are presented. The optimal planning of DC microgrids has an impact on operation and control algorithms; thus, coordination among them is required. A detailed review of the planning, operation, and control of DC microgrids is missing in the existing literature. Thus, this article documents developments in the planning, operation, and control of DC microgrids covered in research in the past 15 years. DC microgrid planning, operation, and control challenges and opportunities are discussed. Different planning, control, and operation methods are well documented with their advantages and disadvantages to provide an excellent foundation for industry personnel and researchers. Power-sharing and energy management operation, control, and planning issues are summarized for both grid-connected and islanded DC microgrids. Also, key research areas in DC microgrid planning, operation, and control are identified to adopt cutting-edge technologies. This review explicitly helps readers understand existing developments on DC microgrid planning, operation, and control as well as identify the need for additional research in order to further contribute to the topic.

INDEX TERMS DC microgrids, renewable energy sources, batteries, supercapacitors, dc bus voltage, power management, state of charge, microgrid operation, planning.

NOMENCLATURE

ANFIS	Adaptive neuro-fuzzy inference system
ANN	Artificial neural network
BSM	Bus signaling method
DCL	Digital communication link
DE	Differential evolution
DERs	Distributed energy sources
DG	Distributed generator
DSM	Demand side management
DSO	Distribution system operator
ED	Economic dispatch
EDC	Extended droop controller
EMS	Energy management system
ESS	Energy storage system
FLC	Fuzzy logic controller
GA	Genetic algorithm
GWO	Grey-wolf optimization
HPFD	High pass filter droop
LBC	Low band width communication
LC	Local controller
LQG	Linear quadratic gaussain
LSTM	Long short-term memory
MILP	Mixed integer linear programming
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MPPT	Maximum power point tracking
PSO	Particle swarm optimization
PV	Photovoltaic
RE	Renewable energy
RESs	enewable energy sources sources
SMES	Superconducting magnetic energy storage
SOC	State of charge
SVR	Support vector regression
UC	Unit commitment
VRD	Virtual resistance droop
VSC	Voltage source converter

I. INTRODUCTION

Nowadays, the use of renewable energy sources (RESs) has become significant due to the continuous depletion of fossil fuel. However, the high-level integration of RESs raises several technical issues, such as low fault ride through capability, high fault current, low system inertia and generation reserve. The international renewable energy agency (IREA) predicts that 66% energy demand will be met by RESs [1]. Among several RESs, solar and wind powers are the most promising due to the low-cost generation as well as maximum power point tracking (MPPT) capability [2]–[4]. However, the direct integration of RESs to the utility grid is a challenging task due to its intermittent nature. A potential solution to the problem is the integration of solar and PV power generators to the DC bus of the DC microgrids [5]–[8].

As a proliferation of RESs and electronically controlled load into the system, the concept of DC microgrids is gaining more attention than conventional AC microgrids due to several benefits. These include that there are no conflicts with harmonics or frequencies, synchronization is not needed in islanded mode, and no issues exist with reactive power control [9], [10]. DC microgrids are mainly divided into two broad categories depending on operating conditions: grid-connected mode and islanded mode. Both the configuration of DC microgrids depends on RESs to reduce the carbon footprint [11], [12]. However, the integration of RESs with DC microgrids reduces the reliability of the system due to the intermittent nature of renewable sources. In order to tackle reliability issues, some fossil fuels, such as diesel or gas are integrated into DC microgrids along with RESs [13], [14]. Although the reliability is increased to some extent, the efficiency may not be significant for DC microgrids unless efficient power management schemes are developed. In one hand, the integration of several energy storage devices such as batteries, supercapacitors can increase the reliability of DC microgrids to a good extent, on the other hand, the control issues become complex for such case [15], [16]. The battery and supercapacitor can be charged during off-peak hours and the stored energy can be delivered to the load during peak hours. Since the battery has high energy density and the supercapacitor has high power density, the complex bidirectional controller designs are imperative to operate them within the DC microgrids.

In DC microgrids, the DC link voltage control and power management among the several sources and loads are the main concerns for the researchers. The conventional droop control of DC microgrids has simplicity in implementation due to the absence of communication link [17]. However, the parameter choice of droop controller may cause DC bus voltage fluctuation and mismatch in current sharing. To resolve these issues of droop control, the hierarchical control with a low-bandwidth communication link can be adopted [18]–[21]. Since DC microgrid observes a huge number of energy storage devices, such as batteries, supercapacitors, it is important to design the controller considering the state of charge (SOC) of these devices. This requires the new design technique of droop controller in which the droop parameters vary based on the SOC. Nevertheless, full control over the output power of ESS will not be achieved due to the variation in droop parameters. Thus, the active power flow in DC microgrids will be compromised and the redesign of the controller will be required for both grid-connected mode and autonomous mode.

Moreover, DC microgrids require coordination between hardware-based control and software-based optimization planning. These requirements are due to continuously varying power generation from RESs and dynamic load profiles [22]–[25]. With regard to factors such as uncertainties, load demand variations, and power generation outage, coordination between planning and control of DC microgrid increases reliability. Several optimization techniques, such as mixed-integer linear programming, robust optimization, linear programming, are adopted in the DC microgrids system planning level to minimize the total operation costs [26]–[28]. Whereas, at the device-level, several control strategies are used to keep the DC bus voltage within specified limits as well as balance the generations and loads. At the operation level, depending on the availability of generating unit, load demand, and the cost of generation, unit commitment (UC) and economic dispatch (ED) are performed to minimise overall cost and maximize profit [29]–[31]. The operation in either grid-connected mode or islanded mode can is decided based on system faults or price signals from the grid operator side. Thus, the proper transition between grid-connected mode and islanded mode is required for smooth operation of the DC microgrids. Several reviews on DC microgrids, especially, on the control, application, and protection of DC microgrids are presented in the existing literature [32]–[34]. For example, the authors in [32] summarized several control and stabilization techniques of DC microgrids. However, the works related to operational constraints of DC microgrids are not discussed in this review. Moreover, the control of several microgrid clusters is barely discussed. In [33], several microgrids topologies are discussed considering practical application aspects. Additionally, the work also sheds light on the protection of DC microgrids. However, neither the planning such as forecasting, topology selection, and energy storage devices sizing nor the economic operation such as unit commitment, economic dispatch, reserve management are broadly discussed in this work. Although the control and protection of DC microgrids considering several clusters are reviewed in [34], the future trend in the developments, planning, and operation of DC microgrids is overlooked.

Considering the importance of the aforementioned issues, this paper provides a broad view of approaches to the planning, operation, and control of DC microgrids and their challenges. Several control strategies, such as centralized, decentralized, distributed, hierarchical, and coordinated control, are well documented in this article. In addition, several optimal planning techniques are also discussed for solving several issues from the DC microgrids system point of view. Several coordination approaches between planning and control are summarized. Some gaps are clearly mentioned in the current studies which could be filled by cutting edge technologies as a form of new contribution from the researchers and industry personnel. This review could be an excellent background for the future development of efficient DC microgrids.

The organization of this paper is as follows: Section II describes the planning methods of DC microgrids; the operations of DC microgrids are documented in section III; different control strategies of DC microgrids and their advantages and disadvantages are summarized in section IV based on contemporary literature. Several challenges in current studies and opportunities are provided in section V. Finally, section VI summarizes the major conclusions of this review of DC microgrids planning, operation, and control strategies.

II. DC MICROGRIDS PLANNING

In the planning and operation of DC microgrids, several issues, such as financial, ecological impact, and reliability, are important. In one hand, appropriate planning of DC microgrids has major impacts on operations. On the other hand, the execution of the designed plan plays an important role in maintaining the reliability and stability of microgrids. DC microgrids can operate both in grid-connected mode and islanding mode. The proper planning of available generation units and load is imperative to increase the reliability of the system when DC microgrids are disconnected from the main grids due to faults, voltage fluctuations, or any other disturbances. The planning cost of microgrids comprises three parts: investment cost, operation, maintenance cost, and reliability cost [24]. The long-term investment cost is calculated annually while the short-term cost is calculated hourly during the planning horizon. The reliability cost is dependent on the reliability index during the planning horizon. The planning model of experimental DC microgrids in University of Naples Feerico II is presented in [35]. The microgrids consist of several generation mixes such as PV, wind, fuel cell, supercapacitor, and battery energy storages, DC loads, smart loads, and electric vehicle (EV) chargers. The planning model for optimal size and location of distributed energy resources (DERs) is introduced in [36]. The planning phases consist of several cases such as base case microgrid planning, DC loads ratio sensitivity analysis, critical loads sensitivity analysis, and market price sensitivity analysis. The optimal size and location of DERs are determined using This work is further extended in [24] by specifying the feeder types. However, both the methods presented in [24], [36] ignore the intermittent nature of renewable energy providing an unrealistic solution. In [37], [38], a mixed-integer non-linear programming model is presented to determine the location and size of micrograms equipment. The first stage of the algorithm is solved using the heuristic technique to determine the microgrids topology, optimal equipment size, and locations. The second stage of the algorithm deals with reliable power flow within the microgrids network. However, the programming model assumes a fixed radial microgrids network.

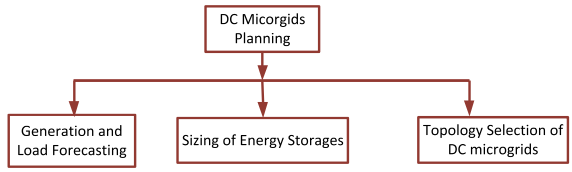

FIGURE 1. Planning methods in DC microgrids.

Another microgrids planning model is presented in [39] to minimize total planning cost with the optimal configuration of microgrids and sizing of DERs. Several methodologies for DC microgrids planning are categorized in Fig. 1.

A. GENERATION AND LOAD FORECASTING

Energy management in DC microgrids is important considering the highly intermittent nature of renewable sources. The variation of power of renewable sources plays an important role in economic operation of DC microgrids. Thus, the forecasting of renewable energy is conducted for DC microgrids while high-level penetration is expected. A back propagation neural network based on modified particle swarm optimization is presented in [40] to forecast renewable energy with the objectives of total cost and power loss minimization. Based on the optimization results, several hybrid distributed generators (DG) are considered to build the DC microgrids model. Furthermore, the load profile variation in DC microgrids may lead to instability. Thus, in addition to renewable power generation, load forecasting is also important from the stability and economic point of view. The energy management system (EMS) requires both renewable energy generation forecasting and load forecasting to provide efficient dispatch strategies. In [41], Markov Chain Monte Carlo sampling-based load forecasting approach for microgrids. The critical loads, residential loads, PV, and energy storages are considered in the microgrids structure in the presented forecasting approach. The load forecasting for a rural microgrid in Africa is presented in [42] with long short-term memory (LSTM) based on support vector regression (SVR). Several factors, such as household types, and commercial entities, are considered as input variables whereas the load

TABLE 1. Different ESS sizing strategies.

Optimization Methods	ESS Types	Objectives	Contributions	Limitations
GA [54]–[56]	Battery	cost minimization	total energy consumption is reduced load management and ESS location	reliability is not improved
MILP [57]–[59]	Not specified	cost minimization (investment and operation)	reduction in power conversion loss	–
DE [60], [61]	battery and supercapacitor	battery life cycle maximization and cost minimization	the micrograds configuration is optimized	SOC is not well managed
Compro mise Programming (CP) [62]	battery	daily worth maximization and cost minimization	effective sizing with minimal cost	system operational requirements are not considered
PSO [63]–[65]	battery	minimization of annualized capital cost, and operation & maintenance cost	loss of power supply probability is reduced,	assumption is made based on limited RES
sensitive analysis [66]	not specified	maximization control performance and minimization power losses	optimal node selection for ESS mitigation of power and energy variation	variation of the grid constructions and parameters are not considered
GWO [67], [68]	battery	minimization net present cost	optimized configuration is selected	–
DP optimization [69]	vanadium redox battery	ESS cost	load uncertainty improvement	PQ issues are unsolved
NSGA-II [70]	hybrid SMES-flywheel	maximize the power delivered, minimize power fluctuation and costs	cost reduction and performance improvement	solution procedure is time-consuming
probabilistic approach [71], [72]	battery	investment cost minimization	optimal size of battery when time-of-use (ToU) is used uncertainties are well handled	sensitivity analysis with random input variables should be investigated
linear programming [73]	hydrogen storage	cost and carbon emission minimization	reduced carbon emission	size of hydrogen storage is larger than battery

profiles are the target variables. An artificial neural network (ANN) based load forecasting model for microgrids is adopted in [43]. The forecasting model considers hourly load data of the previous day, the day type of the week, and the month. Most of the renewable energy forecasting in microgrids is based on the weather data which are also determined based on the forecasting approach. Thus, one forecasting approach based on another forecasting gives inaccuracy. Thus, a persistence technique for both renewable energy and load forecasting is presented in [44] which is based on historical power data instead of weather data. Other techniques presented in the literature for load and generation forecasting include fuzzy logic [45], [46], statistic approach [47], [48], intelligent algorithm [49], adaptive neuro-fuzzy inference system (ANFIS) [50]. However, further accurate load and generation forecasting for DC microgrids can be the future research directions combining those methods or models as a hybrid one.

B. SIZING OF ENERGY STORAGE

Renewable energy-based DC microgrids face instability due to uncertainty in renewable energy generations. However, the integration of an energy storage system (ESS) can ensure the sustainable, resilient, stable, and economic operation of DC microgrids. The planning phase of microgrids requires extensive analysis of optimal sizing of several energy storage devices, such as battery, supercapacitor, magnetic superconducting energy storage (SMES), flywheel storage, pumped storage, and so on. Most of the existing literature mainly focuses on capacity minimization based on optimal sizing of energy storages while other important issues are overlooked. Thus, a comprehensive review is needed to guide the researcher and industrialists on optimal ESS sizing based on several factors. Several studies show that the optimal sizing of ESS can be divided into single objective and multi-objective optimization problems. Most of the single-objective optimization problems are based on cost minimization [51]–[53]. However, the multi-objective ESS sizing has several objectives such as maximizing reliability, minimizing cost and consumption, maximizing life-cycle, and so on. Several optimization approaches, such as heuristic methods including a genetic algorithm (GA), particle swarm optimization (PSO), differential evolution (DE), and grey-wolf optimization (GWO), probabilistic approach, and mixed-integer linear programming (MILP), are adopted for optimal size determination of battery, SMES, hydrogen storage, flywheel storage and so on. A comprehensive list of different ESSs sizing methods is summarized in table 1. The contributions of several studies are highlighted as well as limitations are discussed so that those limitations could be overcome with new approaches.

C. TOPOLOGY SELECTION

The conventional distribution network sees a paradigm shift towards more interacting networks that can incorporate several DGs, ESSs, electric vehicles, constant power loads (CPLs), and renewable sources. The DC microgrids or hybrid DC/AC microgrids interacts within the distribution networks to resolve many problems of conventional distribution networks. However, the structure/topology design of DC microgrids plays an important role which is a major planning problem.

Depending on the planning of DC microgrids structure, operation and control methodologies are developed [74], [75]. The net-zero energy building (NZEB) is a new concept to reduce carbon emission and fossil fuel consumption by integrating more renewable sources which can be implemented with the concept DC microgrids [76]. The topology planning of a vast DC microgrids is presented in [6] for large-scale integration of renewable energy. A hybrid ESS is planned to support DC bus voltage with the use of active topology. A DC dump load is connected directly to the DC bus to protect the ESS from overcharging and stabilize DC bus voltage. The topology of DC microgrids for the rural and urban areas of India is discussed in [77]. The micrograds consist of a radial DC bus connecting renewable sources, diesel generators fueled by biodiesel, domestic and commercial loads, and lead-acid batteries. Sometimes the DC microgrids are merged with AC microgrids to combine the advantages of both and such microgrids are called hybrid DC/AC microgrids [78]. In such a hybrid topology, the DC/AC loads are connected to DC/AC sub-grids to improve the overall efficiency. Another benefit of such topology is the provision for the connection of EV charging station directly to the DC bus [79]. Thus, the topology selection of DC microgrids is an integrated planning strategy that has impacts on both operation and control.

III. DC MICROGRID OPERATION

This section provides a comprehensive review of guidelines for the operation of DC microgrids so as to achieve resilience, security, and good levels of reliability.

A. UNIT COMMITMENT

Unit commitment is necessary to schedule available generating units in microgrids at every time interval based on several factors such as market price signals, load forecasting, availability of renewable energy, and distribution network ancillary service provisions. The unit commitment problem of a microgrid is solved in [80] with an objective to minimize the total generation cost while meeting all load demands within the microgrids. Unlike the conventional unit commitment problem which depends on a priori information, this method is not as more suitable for practical implementation as it does not require prior RES and load information. A day ahead unit commitment operation is solved in [81] using a heuristic optimization technique to minimize the total operation cost and carbon dioxide while scheduling the power among different microgrids units. This approach also effectively eliminates congestion according to congestion signals by optimally scheduling different units. However, the presented unit commitment approach requires energy storage system within the microgrid. Furthermore, several unit commitment approaches, such as stochastic [82], robust [83], mixed-integer linear programming [84], probabilistic [85], and PSO [86], are also presented in the literature. However, further improvement in unit commitment would be possible by combining several methods.

B. ECONOMIC DISPATCH

The next step after unit commitment is economic dispatch in which already connected generating units are operated in such a way that the total generation cost is minimal to meet the load demands within the microgrids. A distributed economic dispatch (ED) problem formulation for DC microgrids that considers communication link delay is presented in [87]. An ED problem formulation is presented in [88] with an objective to minimize the total operation cost. The cost is associated with generation cost in the microgrids, including the utility grids, adding the cost efficiency of the system with the demand response requirements. Since the power flow model is included in the optimization problem, the transmission loss is included as generation ED. A fully decentralized economic power dispatch strategy of DC microgrids is proposed in [89] to improve the scalability, reliability, and economic benefits.

A two-layer control scheme for AC/DC hybrid microgrids is presented in [90] in which the lower-layer represents a continuous dynamic model with a solution analogous to the decentralized economic dispatch solution. The upper layer, consisting of the primary, secondary, and the tertiary controller, is responsible for power exchange between two sections. In DC microgrids, the ED problem is often solved by a centralized master controller to achieve controllability and high accuracy. Since the centralized approach of ED requires an extensive communication network, distributed control schemes with consensus algorithms are presented to realize online optimal generation scheduling [91], [92]. In [93], a power scheduling scheme is presented utilizing deficit/surplus information of lower-level microgrids which is a tradeoff between several contradictory objectives like operation cost, system resiliency, and customer privacy. However, this scheme is based on a strong assumption that the power mismatch is known by all DGs within the microgrids is not achievable in a totally distributed microgrids without a centralized communication facility [94]. Moreover, any communication link faults may degrade the convergence speed of consensus algorithm based economic solution [95]. To resolve these issue, several droop-based control schemes are presented to address the optimal ED in microgrids [96], [97]. In [98], an objective function based droop scheme is presented to trace the variability of distributed resources.

C. RESERVE MANAGEMENT

The inertia of the microgrids is reduced to zero or near zero in case of islanded mode operation while observing high-level penetration of renewable energy. Thus, a reserve power margin needs to be maintained within the DC microgrids. For instance, the PV system cannot provide any inertia to the islanded microgrids, thus, it degrades the DC bus voltage control response. On the other hand, although the wind systems have some inertia, they are effectively decoupled from the DC microgrids system due to the connection of wind turbine through the power electronics converters [99]. To minimize these negative impacts of renewable energy integration into DC microgrids, it is imperative to keep some reserve power by adding sufficient energy storage devices. The state of charge and power management of several ESS and DGs within the DC microgrids can help maintain some necessary reserve power for the smooth operation of DC microgrids. A power management strategy in DC microgrids is presented in [100] to keep the battery state of charge (SOC) within specific limits. Thus, by maintaining proper SOC, the reserve power is guaranteed in the microgrids. Another current sharing approach is presented in [101] to maintain SOC of battery which mitigates power generation and demand mismatch. [102]. Since the energy storage devices are a costly solution to provide reserve in DC microgrids, de-loading techniques are developed for wind and PV systems. In these techniques, the wind and PV systems are operated at a reduced power point level instead of maximum power point level [103]. However, in case of

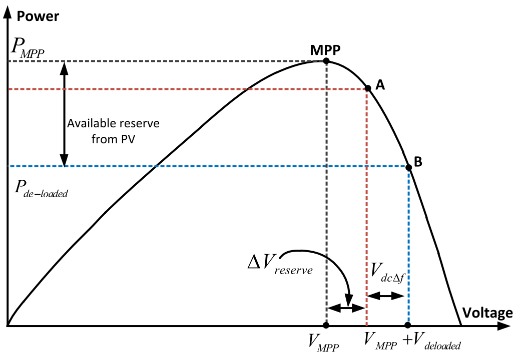

FIGURE 2. Reserve power provided by PV.

emergency power demand, the operating point can be shifted to the MPPT point. As shown in Fig. 2, the PV system is operated at point B instead of MPP. Thus, point B can be shifted to point MPP or any point between MPP and B to provide reserve power in the microgrids. In [104], a coordinated approach to maximize the overall spinning reserve in isolated microgrids is presented by solving a constrained dynamic optimization problem. Since the optimization problem is formulated in a single-level, the efficiency is degraded. Thus, in [105], a bi-level optimization problem formulation is presented in which the upper level represents a microgrids planner whose goal is to minimize planning and operation cost. The lower level represents the distribution system operator (DSO) whose primary objective is to guarantee reliable operation of microgrids by keeping enough reserve power.

D. ON-GRID, OFF-GRID, AND TRANSITION OPERATIONS

In on-gird/grid-connected mode, a microgrid exchanges energy with the utility gird. Depending on price signals, the microgrid injects or absorbs power to or from the grid [106], [107]. In this operating mode, available energy sources are scheduled to minimize the operating costs by employing unit commitment and economic dispatch as discussed above. In case of any grid faults, such as short circuit faults, voltage dip, voltage sag, or converter faults, the microgrid is disconnected from the grid to allow autonomous operation [108]–[110]. However, an intentional islanded operation is also sometimes allowed for the maintenance of grid-connected converters and associated connecting lines.

IV. DC MICROGRID CONTROL

The DC microgrid is connected with the utility grid through bidirectional voltage source converter (VSC) and contains PV and wind systems as the renewable energy sources [111]–[114]. Different types of local loads (resistive and power electronic interfaced), PV panel, energy storage system (ESS), and VSC are connected to the common DC bus as shown in Fig. 3. The DC microgrids controllers are designed so that they can operate either in grid-connected mode and islanded mode. In grid-connected mode, the grid VSC controls the DC link voltage whereas in islanded mode any energy storage device controls the DC bus voltage. The most common energy storages used for DC microgrids are battery and supercapacitor. Due to the higher power density, the supercapacitor controller is designed to buffer the fast fluctuations [14], [115], [116]. On the other hand, the battery has high energy density, thus, the controller is designed to compensate for low-frequency power mismatch [117]. The solar PV and wind connected to the common DC bus can operate either in maximum power point tracking mode or in any reduced power mode depending on the requirements. In grid-connected mode, any power mismatch, either surplus or deficit, is mainly balanced by the grid VSC. However, in islanded mode, sufficient energy storage needs to be installed to balance any power mismatch. In extreme cases, where sufficient energy storage is not available, the load shedding controllers are incorporated with all the loads to switch them on/off for balancing power and controlling DC bus voltage at a predefined value.

Although DC microgrids are evolving in recent years, the control of DC bus voltage and the power management are challenging tasks due to the connection of different hybrid sources and loads in the common DC bus as depicted in Fig. 3. Control strategies used for DC microgrids are summarized in Fig. 4 The basic control strategies for DC microgrids are centralized, decentralized, and distributed controls. In centralized control strategies, the data from several distributed units are sent to the central controller through the communication links, and command signals are sent back to each unit by the central controller. The most well-known and established centralized controller is master-slave controller [118]–[120]. This control strategy has several drawbacks such as single point failure, shorter battery life, and poor scalability [121]. In order to avoid single point failure, and increase battery life, the decentralized controller is presented for DC microgrids [122]. To achieve decentralized control of each unit, the droop controller is adopted in which determining the droop parameters are a challenging task since the current sharing, accuracy, and system stability are highly linked to the droop parameters [15], [123]. For instance, higher droop coefficients result in a more damped system and increased current sharing accuracy. However, the higher value of droop parameters leads to increased DC voltage deviation. The advantages of both centralized and decentralized controller are combined in the distributed controller to achieve several control objectives, such as proportional load power-sharing, autonomous voltage sharing, and state of charge balancing (SOC) of energy storages [124]–[127]. For complex and large-scale microgrids, the hierarchical controller is adopted [128].

In order to achieve a stable operation of DC microgrids, it is important for the power management scheme be able to balance between loads, grids, and distributed generators. Different power management techniques are presented based on the DC bus voltage of DC microgrids. However, the reliability of these techniques is not much because of unwanted

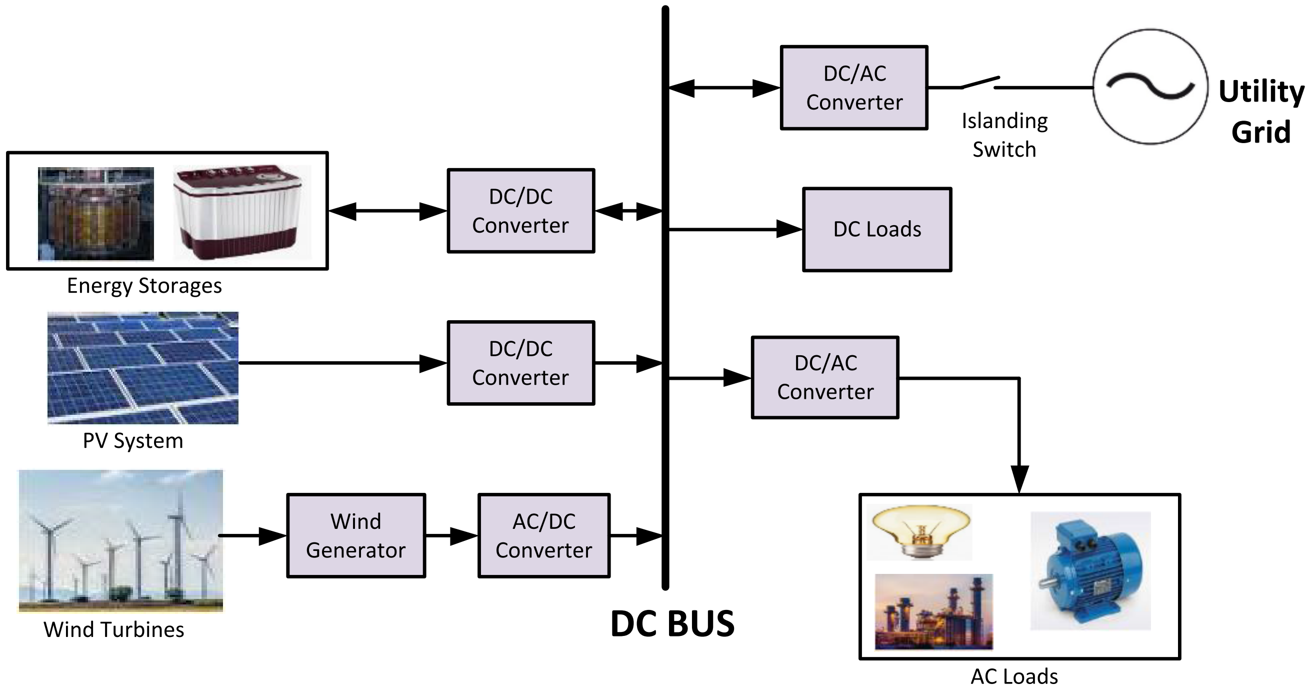

FIGURE 3. Basic components of DC microgrids.

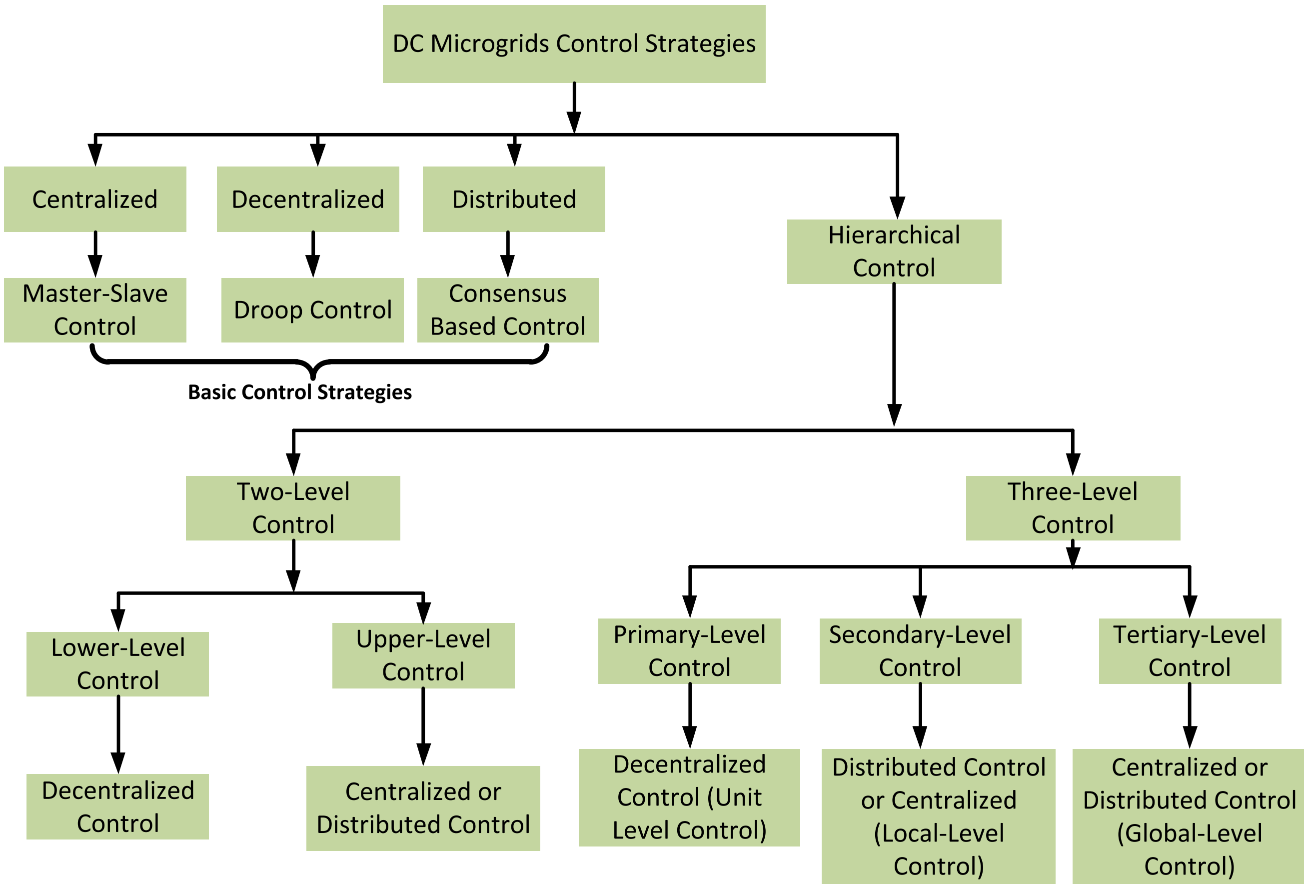

FIGURE 4. Control for DC microgrids.

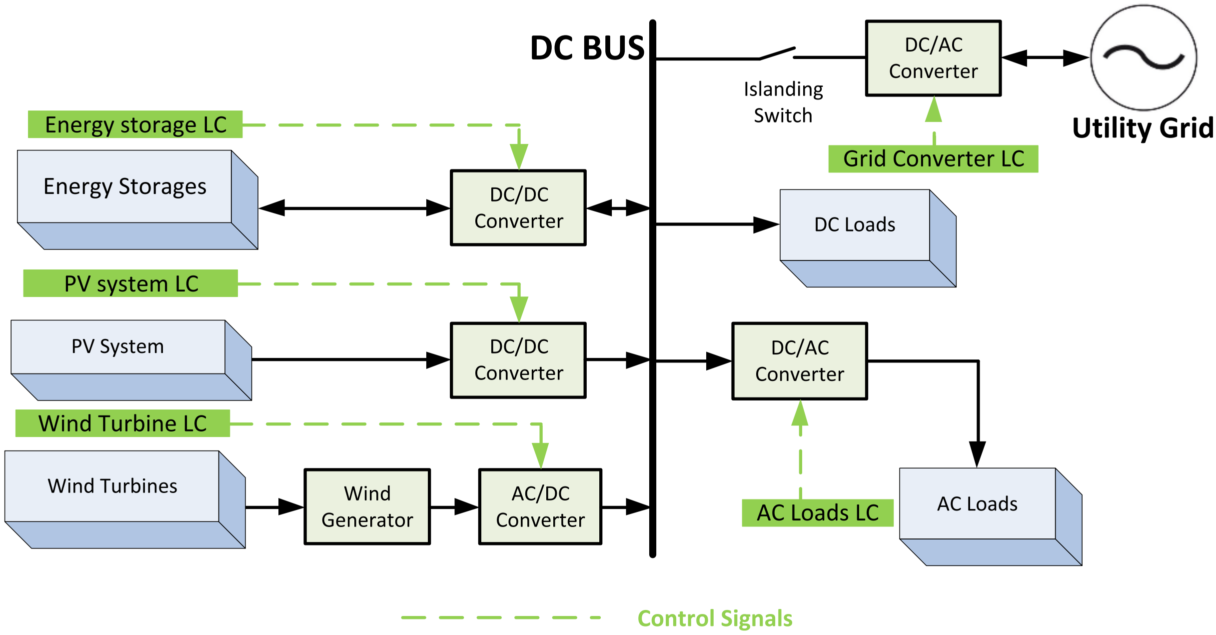

FIGURE 5. **Decentralized controller for DC microgrids.**

switching of sources and load due to the DC link voltage fluctuations [129], [130]. Some other techniques are presented in [131], [132] to handle those issue. These techniques mainly adopt the central control strategy in which several loads and sources are controlled from a control center. Furthermore, the supercapacitor is also used for a smooth transition and battery life cycle improvement. In [32], [133] some simplest DC microgrid control approaches are presented in which power-current or voltage-current droops are mainly adopted without any communication link. However, there is a tradeoff between simplicity and DC bus voltage control. An alternative solution to the problem is to implement the hierarchical control which is presented in [8], [134]. The hierarchical control aims to mitigate this mismatch by adding the secondary or any upper-level control. The state of charge (SOC) of ESS is also used to implement a droop controller to handle the aforementioned problems. The adaptive droop methods presented in [135], [136] vary the droop parameters based on the SOC of the ESS; consequently, it controls the output voltage adaptively. These techniques are mainly applied to design proportional power-sharing among different ESSs. However, the droop parameters variations according to the SOC do not result in full control over the output power of ESS. Thus, the active power flow among several loads and generators is compromised in DC microgrids. The droop technique is mainly suitable for islanded mode operation of DC microgrids. However, in the urban distribution network, the islanded mode operation of droop is rarely expected. Instead, most of the time, the DC microgrids are operated in grid-connected mode except the autonomous mode in emergency cases only. This means that the utility grid is mainly responsible to maintain a balanced power flow in DC microgrids by absorbing or injecting power. Whenever the grid is disconnected from the DC microgrids, the available DGs and ESSs must be capable to balance the power flow in the DC network. The following subsections summarize different control strategies for DC bus voltage control, power management, and SOC restoration in DC microgrids.

A. BASIC CONTROLS

DC microgrid controls are mainly classified into three basic groups: decentralized control, centralized control, and distributed control. The concepts of these control strategies are explained in Figs. 5,6,and 7, respectively.

1) DECENTRALIZED CONTROL

In a decentralized control strategy, all of the associated converters of DC microgrids are controlled by the local controllers (LC). Several locally measured signals are used as input signals to the controllers and processed locally to generate gate pulse for the converters. For example, as shown in Fig. 5, the controller of energy storage devices measures the output voltage and current and uses them as input signals to the controller for generating gate pulse for the bidirectional DC-DC converter. The most common and widely used decentralized controller is the droop technique. To achieve decentralized control of each unit, the droop controller is adopted in which determining the droop parameters are a challenging task since the current sharing, accuracy, and system stability are highly linked to the droop parameters [110], [137], [138]. For instance, higher droop coefficients result in a more damped system and increased current sharing accuracy. However, the higher value of droop parameters

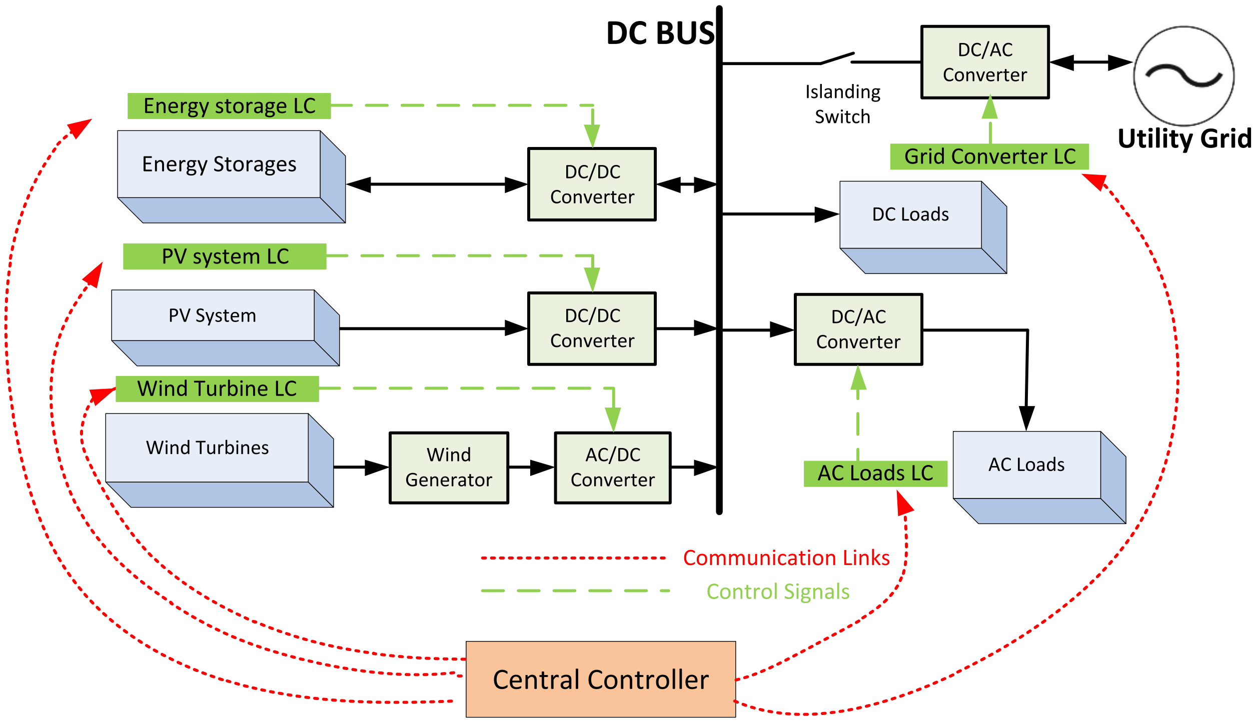

FIGURE 6. Centralized controller for DC microgrids.

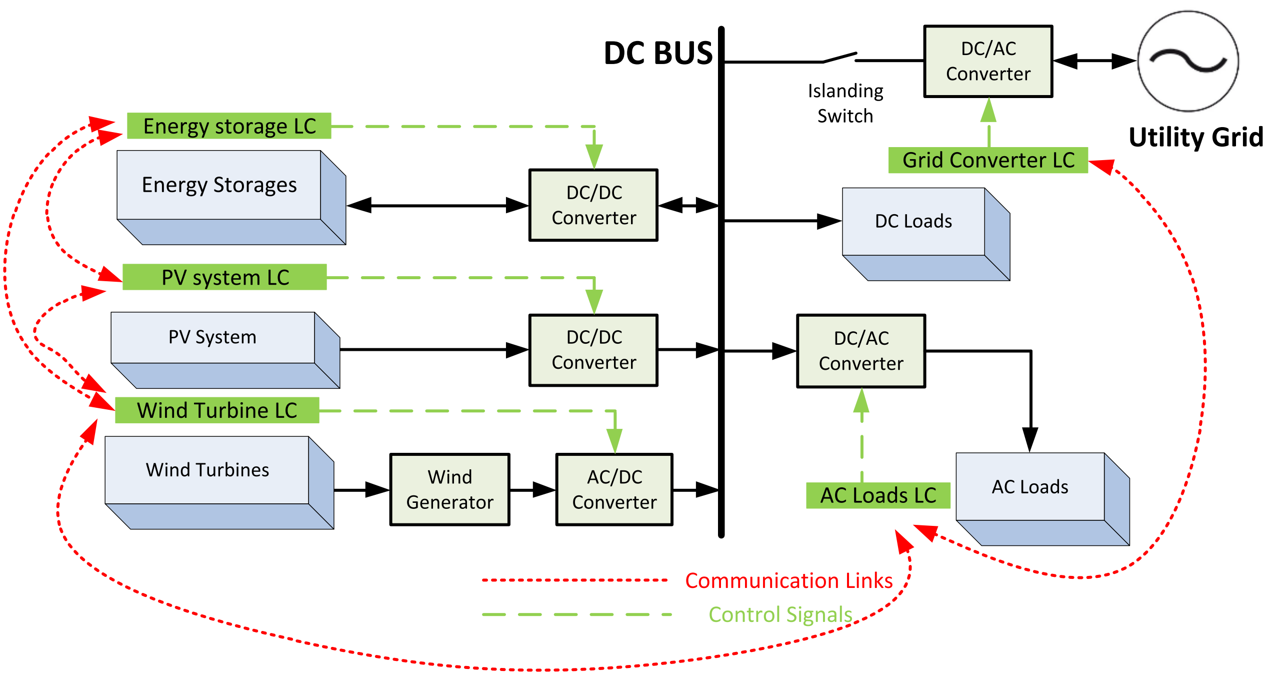

FIGURE 7. Distributed controller for DC microgrids.

leads to increased DC voltage deviation. An extended droop controller (EDC) for islanded DC microgrids is presented in [139] to obtain autonomous power-sharing among several energy storage devices during a sudden load change. The droop controller consists of virtual resistance droop (VRD) for battery and virtual capacitance droop (VCD) for super-capacitor. The conventional droop control has a low DC link voltage issue in case of increased output current. To handle this issue, a low bandwidth communication (LBC) based decentralized control structure is presented in [123] which does not require any centralized secondary controller. Since all the controllers are realized locally and LBC system based controller is activated for changing the DC current and voltage, the decentralized controller is achieved. A decentralized droop-based controller for an islanded DC microgrids is presented in [89] to achieve effective power management, bus voltage restoration, and state of charge (SOC) recovery for energy storages. The battery converter is controlled with high pass filter droop (HPFD) whereas VCD is implemented for supercapacitor (SC). Thus, autonomous power split is achieved in which high-frequency power fluctuation is buffered by SC and low-frequency power is supplied by the battery. A virtual-battery based droop control is presented in [140] for efficient power dispatch and SOC balance. The virtual resistance and reference voltage for the droop controller is determined from the time-varying parameters of ESS. Several decentralized control strategies for DC microgrids are summarized in table 2 showing several research gaps that could be filled with advanced developments and new control technologies.

In table 2, several methodologies are summarized for decentralized control of DC microgrids. It is indentified that several research gaps could be filled with cutting edge technologies and control for further improvement of voltage regulation and power sharing. Although different droop techniques, such as robust droop [150], [151], universal droop [152], distributed droop [153], [154], adaptive droop [155], optimal droop [156], [157], are currently dominant in DC microgrids, further investigations may improve the performance of such controllers.

2) CENTRALIZED CONTROL

The name centralized controller suggests that all the generating and load units within the DC microgrids are controlled centrally in which the communication link is the heart of such controller. The data from several units are sent to the central control unit via the communication link and the control signals are sent back to each unit [158], [159]. The total generations and loads are compared in the central controller and load shedding control signals are sent to the non-critical loads if the generations are not sufficient to serve all loads. The centralized controller has the capability to coordinate different energy sources to meet the critical and non-critical loads [160]. Although such control technique has greater observability and controllability, it faces single point failure issue, less reliability, flexibility, and scalability. A centralized energy management method (CEMM) for hybrid energy storage based system is presented in [161]. Another centralized battery energy management scheme is presented in [162]. An autonomous controller is presented for 10-kW DC microgrids to alleviate the circulating current among different distributed generators using only the DC bus voltage in [163]. Then communication links are extensively used in the smart grid. In [164], smart grid communication links are employed for multi-layer control of DC microgrids which focuses on photovoltaic (PV) constrained production, power balancing, and load shedding. In [121], two centralized control strategies, such as Linear Quadratic Gaussian (LQG) and synergetic controllers, are applied for medium voltage DC microgrids. It shows that both centralized control strategies are capable to stabilize the system in case of large load disturbances. A coordinated centralized controller is presented in reference [165], in which a primary controller based on bus signaling method (BSM) and a secondary centralized controller are coordinated. The controller is capable to strictly regulate the DC bus voltage and maintain the state of charge (SOC) of energy storage devices.

3) DISTRIBUTED CONTROL

The advantages of both centralized and decentralized controllers are harnessed in the distributed controller in which the communication is only made with the neighboring units depending on available digital communication links (DCLs). As shown in Fig. 7, each unit connected to DC microgrids is controlled by the local controllers; however, the local controllers of each unit make communication with neighbors to exchange some information such as bus voltage, the output current of DG, and so on. A nonlinear sliding mode distributed control [166] for hybrid energy storage DC microgrids is presented to achieve asymptotic stability and power balance under variable power generation. The problem of unequal current sharing due to the reduction of DC bus voltage in conventional droop control is resolved in [153] with the adaptive droop and voltage shifting techniques based on the communication of the neighboring distributed units. To reduce the power fluctuation in islanded DC microgrids due to the intermittent nature of PV energy, a distributed control of hybrid energy storages, such as battery and ultracapacitor, are presented in [167]. The ultracapacitor controls the DC bus voltage, whereas the battery controls the SOC of the ultracapacitor. Moreover, the controller adds the difference between the average SOC of the ultracapacitor group and the SOC of one ultracapacitor to its inner current control loop to avoid overcharging or over-discharging. Since in distributed control several units communicate with the adjoining units only, the global power sharing information is not available. Thus, the concept of consensus algorithm is used to dynamic averaging of several variables [168], [169]. These techniques require that unit data be communicated with neighboring units periodically. A distributed droop controller is presented in [170], in which, all units maintain synchronization with the pinned units using pinning based algorithm. However, this method has a high communication burden on several digital channels. Considering the limited bandwidth in microgrids communication, discrete robust distributed control technique [171] and iterative event-triggered communication algorithm [172] are adopted which reduce the communication burden. The maximum load factor (MLF) based improved secondary distributed controller is presented in [173] to achieve an automatic selection of MLF converter. The differential delay algorithm is used to send the MLF signal to the communication link with the shortest possible

TABLE 2. Different droop control strategies.

Control techniques	Contributions	Voltage level in volts	Comments
Mode-triggered droop [141], [142]	Effective power split for islanded PV/hydrogen/battery DC microgrids The controller is robust for different operating modes	60	Battery life-cycle is considered in optimization
Switched current control [143]	Good voltage control and acceptable current distribution Plug-in and Plug-out capability Improved power quality	50	Oscillatory behavior between operating modes can be mitigated using noise filtering Hysteric comparators can be implemented for further improvement
Robust Nonlinear Adaptive [144]	The controller is robust for parameter uncertainty DC voltage is well controlled during external disturbance	48	automatic gain adjustments using artificial intelligence may improve performance
Adaptive coordination control [16], [145]	Peak efficiency of hydrogen production unit (HPU) is achieved Battery life-cycle is improved compared to ref. [141]	48 and 400	High capacity of the battery is required
Robust backstepping voltage control [146]	Robust performance irrespective of uncertainties, unmodeled dynamics, and disturbances Robust performance for different operating conditions Better performance than adaptive and observer-based techniques	750	Constant power load is not considered ESS is not considered in the tested microgrids
Autonomous control [147]	Plug-and-play capability for extending the energy sources.	410	This work can be extended for cluster of DC microgrids The modification of this controller is required for different MPPT controllers
Globally-decentralized control [148]	Better frequency synchronization Improved power sharing for different DC loads	300	Further research is needed for complex microgrids with such control
Sliding mode control [11], [149]	Voltage regulation is achieved with unknown load demand Optimal current sharing	400	Line impedance may degrade control performance

delay period. Thus, the communication link burden is reduced since only the MLF signal is sent to achieve concomitant power-sharing.

B. HIERARCHICAL CONTROL

Hierarchical control of DC microgrids is designed to coordinate control of several energy storage devices, different distributed generations, loads, and renewable energy sources with a functionality-based generic structure which mainly has three control levels such as primary, secondary, and tertiary control. The primary controller, the faster controller compared to the secondary and tertiary controller, is mainly the local controller which utilizes local measurements to restore the DC link voltage and ensure concomitant power-sharing in steady and dynamic conditions at the bottom level of microgrids. The secondary controller with a response time higher than the primary controller is employed to compensate for the voltage deviation resulted from the primary controller. It also tries to minimize the power imbalance with a proper sharing of power among the several DGs. On the other hand, the tertiary controller is the top-level controller with the most slower response time. The main function of this controller is to maintain optimal operation of several units within the microgrids, and between grid and utilities [8], [174]. Three basic controllers are used in the hierarchical, based on specific requirements, in order to overcome their individual shortcomings [175].

1) PRIMARY CONTROL

As discussed above, the primary control is mainly responsible to control DC link voltage and maintain proportional power-sharing in DC microgrids. The most common primary controls are DC-bus signaling, fuzzy logic control, master-slave control, and droop control. The concept of DC-bus signaling has been evolved with the DC bus voltage as an information carrier to regulate DC link voltage and manage active power within the DC microgrids without any communication link. In this method, each converter has a predefined threshold voltage which is used to operate the converter either in power absorbing or delivering mode. In [176], a DC-bus signaling method is presented with DC-link voltage as an information carrier to dictate the different operation modes of microsources. The controller also considers load management with load priority level in case of abnormal or islanded conditions. The DC-bus signaling methods also enable demand side management (DSM) by absorbing/injecting power from/into the DC bus [177], [178]. In such a case, the DC voltage caries the system load information is allowed to vary within a narrow range. The increased system load level or decreased renewable power generation imply the lower DC bus voltage [179], [180]. A control algorithm for PV systems employing DC-bus signaling is presented in [181] which allows a smooth transition for the reference current of the interface as the mode of operation. The power control method for modular PV converter is presented with DC-bus signaling methods which provides a smooth transition between constant power mode and maximum power point tracking (MPPT) control mode [182]. Although the voltage deviation is a major drawback of the DC-bus signaling method, it is widely used for primary control to improve reliability, steady-state performance, and dynamic performance [183], [184].

The fuzzy logic controller (FLC) is presented for battery storage based DC microgrids to manage energy demand in [185]. However, in order to manage the energy demand, high peak charging/discharging of battery degrades its life cycle. Thus, in order to overcome this issue, an FLC is proposed for battery-ultracapacitor based microgrids [186]. The FLC controls the ultracapacitor to regulate DC bus voltage and manage power flow between hybrid ESS and DC links. The droop control cannot provide concomitant power-sharing if the multiple ESSs with different SOCs and distributed generation with different profiles are connected to the DC bus [187]. An alternative solution to this problem is to implement FLC in order to achieve proportional power-sharing for multiple ESSs and DGs. Since the FLC does not require any prior knowledge of the system mathematical knowledge and historic data. This has made the FLC the most popular intelligence control among the other techniques [188].

2) SECONDARY CONTROL

The primary controller is not sufficient to completely manage DC microgrids due to poor voltage regulation and power-sharing. Especially, the performance of the primary controller is not satisfactory in case of large line resistances of long feeders [123], [189]. Thus, the hierarchical technique employs a secondary controller in addition to the primary controller [190]. In the secondary controller, all the basic controllers, such as centralized, decentralized, and distributed, can be implemented with the objectives to provide voltage and current reference signals to the primary controller [129], [191]. The reference signals for the primary controller provided by the secondary controller augment the reliability, proportional power-sharing, voltage regulation, and overall power quality of DC microgrids. In the centralized secondary controller, it is assumed that all the loads are localized at a common, and its voltage is regulated to a predefined value. A central controller measures the common DC bus voltage and sends it to the voltage controlled converters. In the centralized controller, due to the presence of the communication link for the central controller, the resilience and reliability are questionable. Thus, some of the secondary controllers employs distributed control technique [192]. In this approach, the voltages of some buses are communicated with the neighboring converters. Then, the average voltage of these buses is controlled by the secondary controller. In [193], separate average voltage and current controllers based distributed secondary controllers are presented. In [190], the current and voltage information is transmitted to average current and voltage controllers to improve the voltage regulation and current sharing. Since this method is based on droop control, it is not suitable for DC microgrids having long DC cable, since the unmatched line impedance leads to a larger voltage deviation. To resolve this issue, a distributed secondary controller is presented in [194] with consensus-based algorithm instead of droop control. The decentralized controller is also implemented as a secondary level controller for the hierarchical approach due to its relatively less complexity and minimal communication requirement [195]. It mainly performs local control tasks based on local measurements for individual converters. Although the implementation of the distributed approach for the secondary controller is straight forward, the error correction term provided by this method does not match the required correction term, thus, the control performance may degrade [135], [194], [196].

3) TERTIARY CONTROL

The tertiary controller is an additional controller used to achieve economic operation and overall regulation of microgrids. Although the size of the microgrids is very small compared to the conventional grid, the need for efficient economic dispatch and power flow is mandatory which is possible by the tertiary controller. The power management between the microgrids and conventional grid, within several microgrids cluster, and among the several DGs of the same microgrids are the main tasks of the tertiary controller [34], [197]. The tertiary level controller employs several heuristic techniques, such as particle swarm optimization (PSO), and genetic algorithm (GA), for microgrids scheduling [198]–[200]. The consensus-based algorithm is also used for tertiary control of DC microgrids [201]. In a cluster of microgrids, a distributed tertiary controller is presented to provide the voltage set point of individual microgrids and balance the loading of all converters [202]. However, the SOC management among the several units of the cluster is not considered. To overcome this issue, a tertiary controller is presented for SOC management based on the reference current [203]. The tertiary control is also designed for higher efficiency and lower energy loss [204]. However, in this work, one of the converters supplies most of the load current during the light load conditions which degrades the life-time of the converter. Thus, another tertiary control controller is designed [205] to distribute the total workload among the several converters. However, such methods require further research and investigation in order to reduce computational delay in the case of a large number of units in the microgrids.

V. DC MICROGRIDS PRACTICAL PROJECTS

The development of DC microgrids in real life and laboratory has been evolved in recent years. This development helps to meet different customer loads, such as residential, industrial, and commercial, with different voltage levels. The DC microgrid is mainly implemented for static and residential loads with power line as a communication medium [206], [207]. Several DC microgrid projects have been implemented around the world considering different load voltage levels. For example, the original microgrid project of Lawrence Berkeley National Laboratory (LBNL) was designed for standard 480VAC [208]. Later, this project was migrated to 380VDC for the compatibility of the residential load. In [209], New York City DCMG project is demonstrated with a load voltage level of 350V. A comprehensive list of DC microgrids projects installed in several countries such as the United States of America (USA), United Kingdom (UK), Australia, France, Italy, China, and so on [210]–[213] is provided in the Table 3.

The DC microgrids projects are demonstrated by adopting classical distribution network components. Nevertheless, the integration of these components including different loads is more complex than expected. Therefore, several projects installation demonstrated that further extensive analysis is required to set general guidelines and recommendations for researchers and developers in order to overcome main operational and technical challenges.

VI. CHALLENGES & FUTURE RECOMMENDATIONS

Nowadays, DC microgrids provide several technical benefits compared to AC microgrids such as more easily mitigated harmonics, easier integration of renewable energy sources, no frequency, and reactive power control issues, direct connection of consumer loads to the DC bus. However, many technical issues, complex controller, difficult planning and operation, power and SOC imbalances, high fault current resulting from the short circuits, greater uncertainties due to the varying nature of wind speed and irradiance, are observed in DC microgrids. Thus, system planners and operators need to plan and operate DC microgrids carefully to maintain flexibility, reliability, and stability. Nevertheless, several techniques and cutting-edge technologies are continuously being developed to deal with new challenges in implementing DC microgrids. For example, advanced planning methods, efficient operations, improved power, and current sharing techniques, efficient DC bus voltage restoration, optimization techniques are being developed and implemented to handle those issues. However, there are still possibilities to develop better planning, operation, and control strategies as summarized below. Extensive research can be conducted in these directions to develop better planning, operation, and control of DC microgrids.

- Efficient planning and operations of DC microgrids require proper modeling of the system. Therefore, considering the stochastic nature of the integrated DGs in the microgrids, the new or improved model can be developed to reduce the planning and operation costs. Nevertheless, most of the planning model of DC microgrids does not consider real-time operation scenarios. Thus, more research should be conducted on planning that is suitable for real-time operations of DC microgrids.
- Several advanced control techniques, such as adaptive, model predictive, robust, optimal, can be redesigned/improved to guarantee concomitant power-sharing and efficient DC bus voltage regulation of microgrids.

TABLE 3. DC microgrid projects in the world.

Project Name/Country	Year	Toal Capacity in MW	Storage type	Load type
CESI RICERCA DER Testbed/Italy	2006	0.5	Battery and Flywheel	Residential
University of Miami Project, Florida/USA	2007	0.01	Battery	Residential
University of Nottingham Testbed/ United Kingdom (UK)	2011	0.5	Battery	Residential
Queensland University of Technology (QUT) microgrid testbed/Australia	2010	0.015	Battery	Residential
UT Compiègne(UTC) Testbed/France	2011	0.01	Battery	Not Mentioned
Seville Testbed/Spain	2012	0.01	Battery	Residential
New York City DCMG project/ USA	2016	0.016	Battery	Residential and Commercial

- Although redesign/improvement of the controller can have a positive impact on the stable and reliable operation of DC microgrids, it is still vulnerable to the DC link faults. This is because DC-link capacitors are discharged sharply during short circuit faults. Thus, new research can be conducted in improving DC link fault blocking capabilities or improved protection schemes for DC link faults.
- The integration of high-level RES with the DC microgrids reduces the overall inertia of DC microgrids which degrades the voltage control performance. Although some control strategies are developed to tackle such a situation, still more works should be conducted in this direction considering the fact that the DC microgrid is becoming 100% renewable energy-based system.
- The DC link voltage control of microgrids is analogous to the frequency control on the conventional grid. In general, the DC link consists of capacitors and the AC side of the inverter is interfaced inductors. The energy storing capacity of these two devices can be used or coordinated to control the DC bus voltage of microgrids. Very few researches have considered these issues.
- Several storage devices important for power management and DC voltage control of DC microgrids. However, most research does not consider the lifetime of these storage devices. Thus, further work can be done in the direction of life-cycle improvement of energy storage devices while managing power balance and restoring DC bus voltage.

VII. CONCLUSION

Although the DC microgrids have recently been getting more attention due to their potential benefits, it is still a challenging task to design efficient planning, operation, and control algorithms for such systems. The challenge is due to the large-scale integration or RES, power balance, energy management, and DC link voltage regulation while considering planning, operation, and control. This article offers an in-depth and comprehensive critical review on planning, operation, and control of DC microgrids from the aggregated point of view which could help further development in the area. Islanded and grid-connected DC microgrids have been critically reviewed with recent literature. The basic control strategies, decentralized, centralized, distributed, and advanced higher-level controllers have been broadly discussed, along with the planning and operation of DC microgrids. This review has concluded that real-time planning, advanced higher-level controller for concomitant power sharing and voltage regulation, coordination between capacitor and inductor storing capacity, and life-cycle improvement of ESS need further research. The identified gaps in the planning, operation, and control of DC microgrids can be bridged with cutting-edge technologies and new research. This review article can provide excellent guidelines to understand major planning, operation, and control of DC microgrids. Lastly, a list of future recommendations has been provided in DC microgrid planning, operation, and control to guide interested readers.

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