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REVIEW

DC-based microgrid: Topologies, control schemes, and implementations

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and Energy management system

Abstract This article presents a state-of-the-art review of the status, development, and prospects of DC-based microgrids. In recent years, researchers' focus has shifted to DC-based microgrids as a better and more feasible solution for meeting local loads at the consumer level while complementing a given power system's reliability, stability, and controllability. DC microgrid has an advantage in terms of compatibility with renewable energy systems (RESs), energy storage, modern electrical appliances, high efficiency, and reliability. However, the integration of different distributed generations has complicated the control of bus voltage and current. Therefore, several efforts have been made in the research community to further explore efficient control techniques for a reliable and stable DC microgrid. In spite of the numerous review papers published on DC microgrid control, so far, not any has given sufficient emphasis on the power flow analysis methods used in various DC microgrid topologies and the hybrid control topologies discussed in this review. In general, this paper presents a meticulous explanation of DC microgrid architecture; power flow analysis; control strategies with comparative analysis; challenges with recommendations; as well as classical and intelligent-based energy management strategy (EMS). Finally, suggestion for further research is presented. This review paper will go a long way in helping readers to understand the present state of development on DC microgrid control.

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Nomenclature

$G_i(s)$	Transfer function
I_o	Output current
I_{ref}	Reference current
r_{di}	Droop gain
R_o	Output droop resistance
T_i	Integral constant
V_o	Output voltage
V_{ref}	Reference voltage
w_{Lpf}	Cutoff frequency of low pass filter
$\Delta V_{o,max}$	Maximum DC bus voltage derivative

Abbreviation

AC	Alternating current
AI	Artificial intelligence
ANN	Artificial neural network
BES	Battery energy storage
CMA	Covariance matrix adaptation
CPLs	Constant power loads
DC	Direct current
DCL	Digital communication line
DCMG	DC microgrid
DER	Distributed energy resources
DESs	Distributed energy sources
DG	Distributed generation
DRL	Deep reinforcement learning
EMS	Energy management strategy
ES	Energy storage
ESD	Energy storage device
ESS	Energy storage system
ETAP	Electrical transient analysis and program
EVs	Electric vehicles
GA	Genetic algorithm
GHG	Greenhouse gas
HES	Hybrid energy storage
HPU	Hybrid power unit
HSR	Hybrid stochastic robust
HVDC	High voltage direct current
IED	Intelligent electronic device
IoT	Internet of things
LCB	Low communication bandwidth
LV	Low voltage
LVDC	Low voltage direct current
MAS	Multi agent system
MDS	Multi sample differential protection scheme
MG	Microgrid
MILP	Mix integer linear programing
MIP	Mix integer programing
MIMO	Multiple-input and multiple-output
MPC	Model predictive control
MPPT	Maximum power point tracking
NREL	National renewable energy lab
PEC	Power electronic converter
PF	Power flow
PFA	Power flow analysis
PI	Proportional integral
PLC	Power line carrier
PnP	Plug and play
PSO	Particle swamp optimization
PV	Photovoltaic
RE	Renewable energy
RESs	Renewable energy sources
SoC	State of charge
SS	Storage system
TESS	Thermal energy storage
TT	Tidal turbine
WBSEB	West Bengal state electricity board
WOS	Web of science

Contents

1. Introduction

The growing concern about global carbon emissions and energy security has necessitated the search for clean, environmentally friendly renewable energy sources for power generation using the microgrid concept. A microgrid is an emerging technology that encompasses different distributed energy sources (DESs), storage units, power electronic converters, and electrical load.

The most recent developments in power electronics have enabled DC microgrids to meet the required specifications at a reasonable cost and in a smooth approach. Therefore, DC loads are used extensively for industrial applications and residential applications such as a Datacenter, Telecommunication, Electric Vehicles (EVs), DC-powered houses, Electric ships, Renewable Energy Park, rails, Hybrid Energy storage systems, and zero-net electrical energy buildings [1,2]. Through a power electronic interface, it is also easy to effectively connect energy storage devices to the DC microgrid.

The major problems of microgrids are stability, bidirectional power flow, modeling, less inertia, the effect of load perturbation, and uncertainties [3,4]. To address all the aforementioned issues, control strategies have been proposed; however, the control strategies have many limitations, including weak dynamic response, trade-off between voltage regulation and current sharing, chattering, and inaccuracy. Operating the DGs in accordance with the load requirement needs suitable control techniques and power electronic converter selection. Distributed energy sources (DESs), storage units, and electrical loads are all linked to the bus in DC microgrid. Power electronic converters (PEC) connect the DC microgrid to grid utility as depicted in Fig. 1. with several voltage levels and energy storage devices on the DC side that control demand variation, a DC microgrid can deliver power to DC and AC loads[5].

DC microgrid has just one voltage conversion level between every dispersed sources and DC bus compared to AC microgrid, as a result, the whole system's construction cost has been decreased and it also simplifies the control's implementation [6,7]. Nevertheless, researchers across the world are still looking for a way to reduce the cost of manufacturing, improve the performance and maximizing the utilization of renewable energy sources because of numerous advantages of DC microgrid over AC microgrid. In addition to that, they are also seeking to come up with an innovative structures, smart control techniques, stabilization methods, enhanced power flow study and standard requirement for DC microgrid [8]. A suitable robust control system aimed at continuous and foreseeable actions is a critical condition for a microgrid utilizing any bus topology. Sustaining effective and safely delivering essential power from distributed generators to the destination is the primary goal of employing a robust DC microgrid controller. DC microgrid controller needs to carryout numerous control action including voltage and current regulation as well as energy storage synchronization [9].

This review paper is inspired by the recent increase in the deployment of DC microgrid systems for real-world residential and industrial application. Consequently, the paper provides a

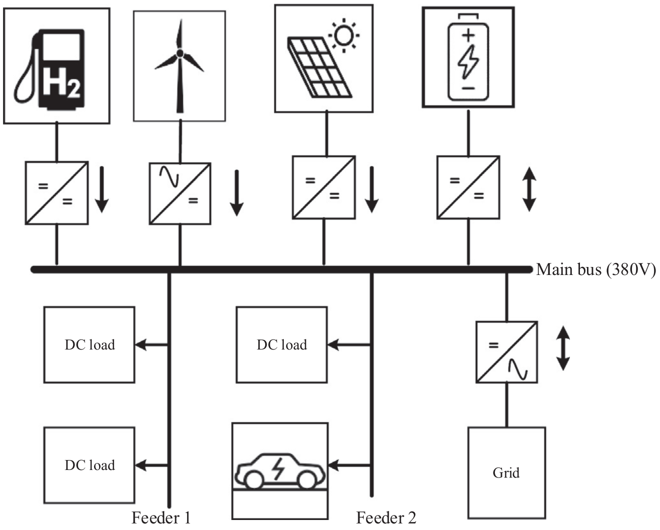

Fig. 1 DC microgrid topology.

current review of the literature on DC microgrid topologies, power flow analysis, control, protection, challenges, and future recommendation. Some research problems were also mentioned and then suggestions on future research were made which can be accomplished by a novel technique or an improvement on the existing technologies by the research community or industries.

1.1. Review screen method

This section describes the methodology used to identify and select papers on DC microgrid control from the literature. Two major academic databases, Scopus (https:///www.scopus.com/) and Web of Science (WOS) (https:///www.webofknowledge.com/), were used to search for relevant prior studies using a series of keywords for a detailed literature review. The keywords used for the search include "DC microgrid", "control strategies", "energy management", "DC microgrid protection", "microgrid topologies", "power flow analysis in DC microgrid", as well as all their possible combinations.

The relevant literature search was also not restricted to a specific timeframe. Having excluded articles relating to only AC microgrid control and energy management system from the database to provide a balanced and objective assessment of only DC microgrid control and energy management strategy, the initial results yielded 256 articles in the WOS database and 287 in the Scopus database. Subsequently, the data were merged and then the articles were limited to journal articles and conferences using certain inclusion and exclusion criteria as shown in Fig. 2a. One filter is used to exclude article that are not directly related to DC microgrid, articles published in books, PhDs, Master dissertation and *meta*-analysis. Furthermore, abstract, and full manuscripts that require a subscription fee are not accessible. EndNote software was used to find and remove duplicates. This is followed by scanning the content of the abstract and conclusion sections to evaluate the relevance of the paper to the objectives of this review study. Accordingly, the publications were chosen based on the scope of this research. Also, only research studies that focused on DC microgrid topologies, control strategies, power flow analysis, protection, energy management as well as the challenges and open research issues related to DC-based microgrid control were considered. This reduced the number of articles down to approximately 210.

The remainder of the sections of the paper is organized as follows: DC microgrid topologies as well as their applications is presented in section 2. Power flow analysis is presented in section 3. Overview on DC microgrid control structures namely, centralized, decentralized, and distributed control each with their advantage and limitation are discussed in 4. Hierarchical control structure, the development in primary, secondary and tertiary control layer as well as energy management strategies in DC microgrid are discussed in section 5. Protection schemes is discussed in section 6. Section 7 highlighted the challenges of DC microgrid with suggestions on the way forward. Section 8 contains a general discussion of the review. Finally, section 9 brings the review to a close alongside recommendation for improvement on the existing research area. Fig. 2b shows the pictorial representation of the review methodology implemented in the article.

2. DC microgrid topologies

The choice of an appropriate DC microgrid topology is critical because it has an impact on critical aspects of a power system such as flexibility, cost, reliability, controllability, robustness, resiliency, and scalability. The voltage level is an important

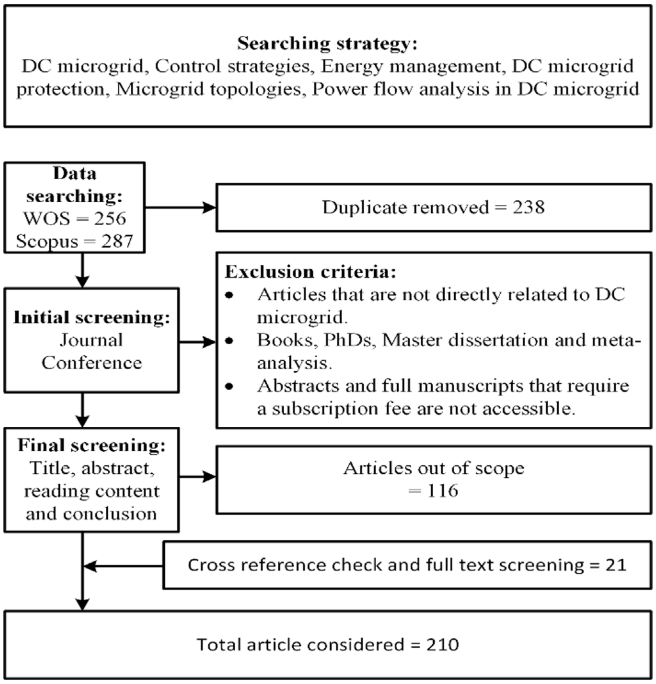

Fig. 2a The literature screen process.

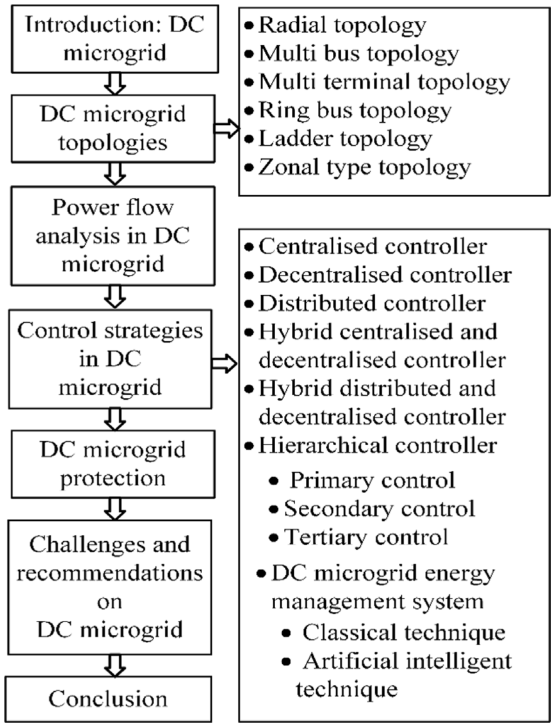

Fig. 2b Pictorial description of the review flow implemented.

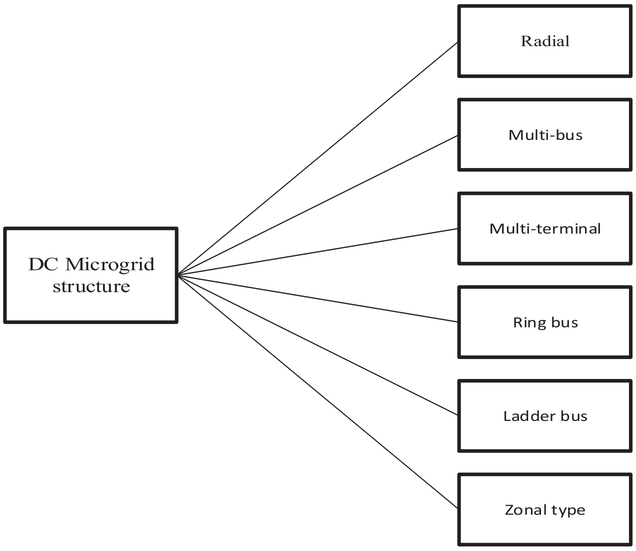

Fig. 3 DC Microgrid topologies.

consideration when designing the topology of a DC microgrid [10]. The available microgrid system topologies are classified into six different types as shown in Fig. 3.

2.1. Radial DC microgrid topology

The concept of radial DC microgrid topology is depicted in Fig. 4. This type of topology is equally referred to as single bus structure or a feeder topology. It is characterized by a single DC bus and a single point of connection for generation, storage, and load in the system. In this type of configuration, the load can only receive power if all its interfaces are operational. Because the system contains other sources and energy storage devices, the inability of a generation interface to function does not always result in a total power outage. Depending on the purpose and requirements, the radial DC microgrid bus could be unipolar or bipolar. This configuration is common in residential buildings because majority of the appliances uses low voltage, therefore, low DC bus voltage is preferred while avoiding additional chopper conversion stages. In this configuration, loads and AC power converters can be placed nearby each other to decrease the distribution losses. The system's reliability can be improved by employing multiple battery stacks [9,11].

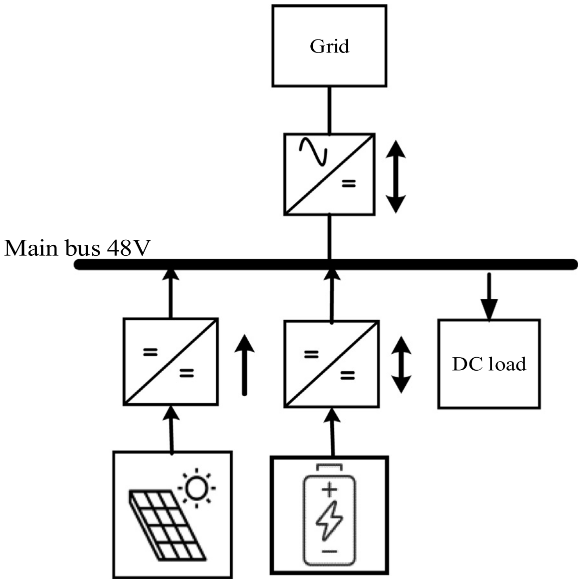

Fig. 4 Radial topology.

2.2. Multi bus topology

The single line diagram of a multi bus topology is depicted in Fig. 5, it is an expanded version of radial system topology that provides increased reliability, efficiency and energy density at perhaps lower cost of installation and operation [12] compared to radial system topology. It is characterized by a redundant feature, as such, it is used in naval ship application. Power can be exchange between two neighboring group of microgrids known as microgrid clusters whenever there is a power deficit or excess. Furthermore, depending on the topology in which the microgrid was linked, faulty buses can be automatically isolated from the system in the event of a failure. Power exchange between multi DC busses are controlled by applying suitable voltage deviations [13].

2.3. Multi terminal topology

Initially, multi terminal topology was proposed for use in direct current at high voltage (DC) systems as in offshore wind power generation. Fig. 6 shows the structure of the multi-terminal DC system. Several input terminals feed the DC supply system. An AC-DC converter connects two or more AC grid interface to the DC grid. The flow of power in multi ter-

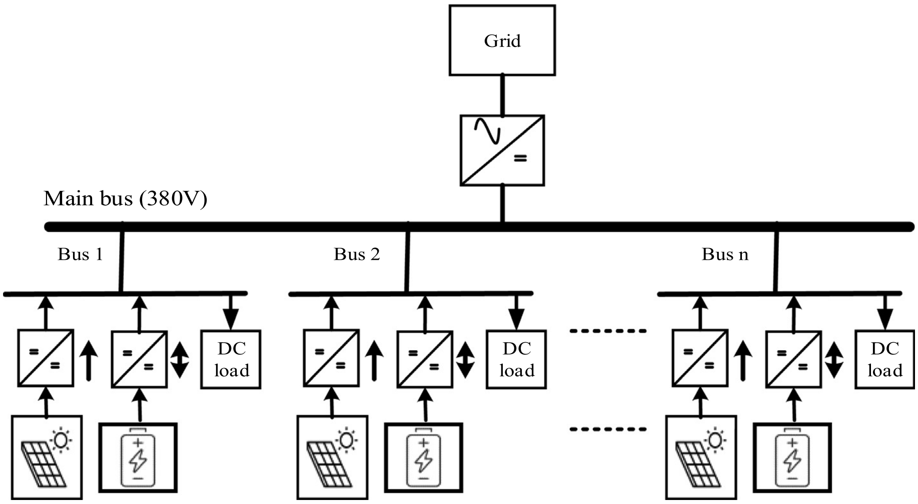

Fig. 5 Multi bus topology.

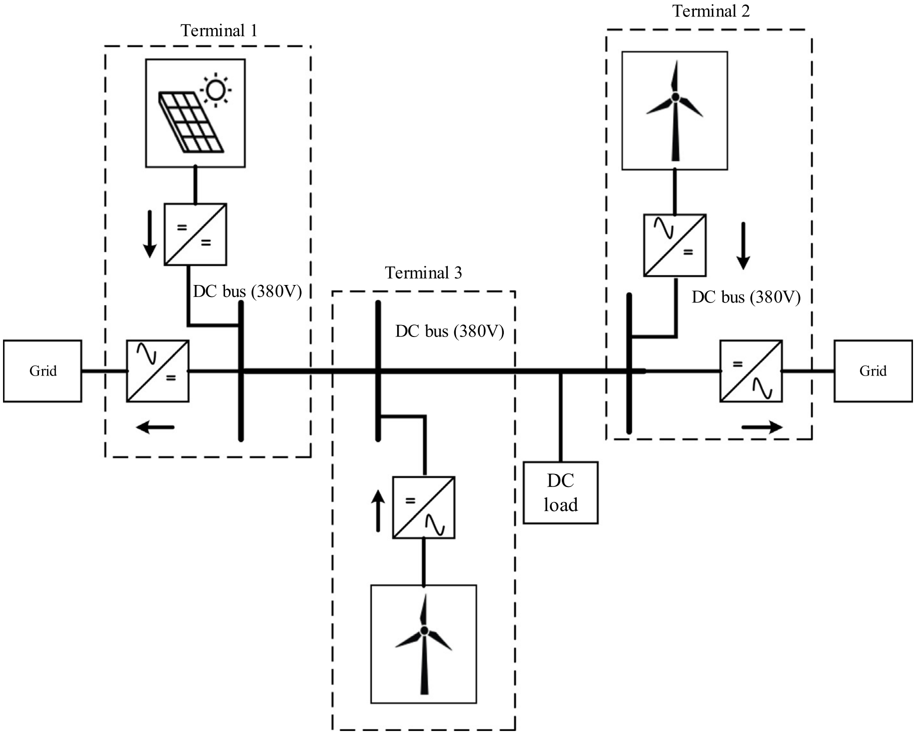

Fig. 6 Multi terminal topology.

minal DC microgrid topology is more complicated compared with the conventional radial system configuration. However, because the system connection allows for multiple power transmission paths, it can also be flexible. The system aims to achieve balance of power sharing between system units, as well as lowering the scheme's voltage and frequency deviation. Voltage source converters are employed to automatically balance power mismatch if the system available power is less. The major aspect that should be considered when designing multi terminal DC system is the protection of the systems as it becomes further difficult when several sources are integrated into the system [13,14].

2.4. Ring bus DC microgrid topology

To overcome the constraints of the radial bus topology in terms of flexibility and fault management, a loop or ring type distribution system can be used. The main idea of the ring type topology is represented in Fig. 7. The suggested solution consists of connecting generations, storage, and load units all on a single ring. Protection switches are placed before and after each bus on the ring for safety reason. This implies that each component of the system has two possible ways of connecting or disconnecting from the ring along the line on each bus's left and right sides. Intelligent electronic device (IED) is employed

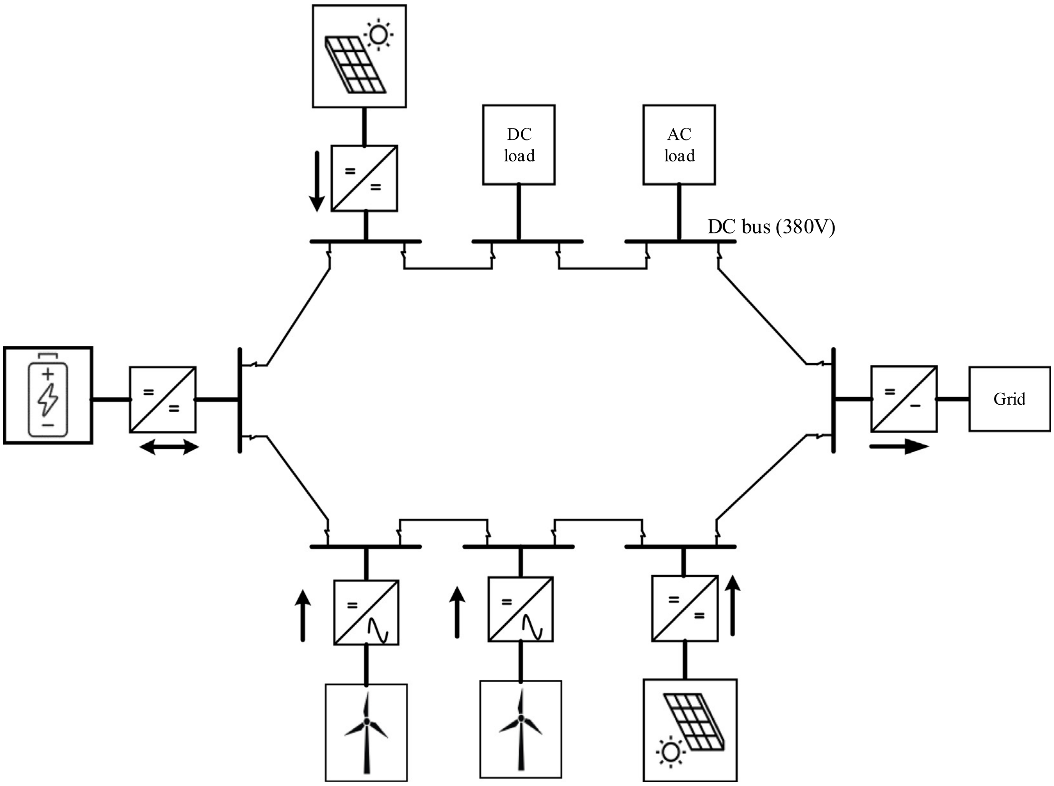

Fig. 7 Ring topology.

as a controller for each bus, as well as its interface with additional neighboring buses. Whenever there is a problem with any bus, intelligent electronic device will first detects the fault and then isolate the faulty bus and provide an alternate route for supplying power to consumers [15]. This kind of supply system was used in cities and industrial settings. This topology is more dependable than the radial topology because it offers flexibility to DC microgrid in such a way that when a fault occurs, the corresponding switches separate it, allowing each units excluding the faulty-one to continue to function. Because of its flexibility, ring topology provides high resiliency, reliability, as well as redundant operation of the system [16].

2.5. Ladder topology

A ladder topology is designed in the form of a ring, with distributed energy sources, energy storage units, and loads connected in relation to ring of the laddered topology [17]. Two buses are connected to the ring of the ladder as shown in Fig. 8, whichever one can provide DC power to the ladder's other rings. In this way, network stability is significantly improved. This type of system topology has the highest redundancy compared with other type of system topology and that has made the system capable of eliminating open circuit fault as well as single point failure and achieve high availability [11,18]. The topology also offers better fault management because whenever a fault occur, the faulty part alone can be isolated with the help of the switch and the remaining system continue to normally function [19]. [20] presents a multi-level ladder topology for producing a large amount of output voltage levels, the simulation results of comparison shows that the suggested cascade topology might overcome the weaknesses of other topologies.

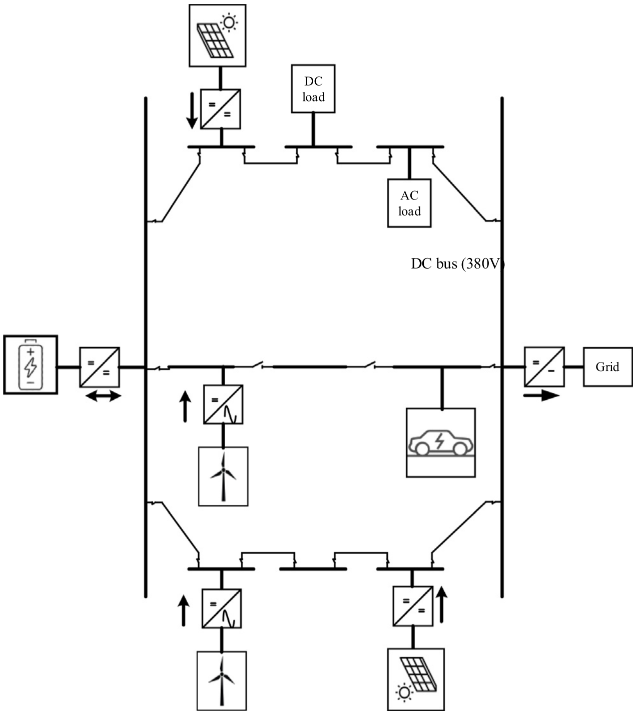

Fig. 8 Ladder topology.

2.6. *Zonal topology*

In zonal topology, zones are created within the microgrid system each with its protection and load center. To improve the system's reliability, [21] proposes a zonal electrical distribution system for large ships. The idea behind zonal microgrid topology is depicted in Fig. 9. Numerous system elements such as generations, energy storage units, power electronic converters and switchgears are contained in zonal DC microgrid configuration with the goal of delivering power to a collection of loads. Two redundant DC buses serve each zone, which are powered by the grid utility as well as sources of distributed DC and AC. The zonal topology provides numerous options for delivering power to the consumer. Electrical energy can be delivered simultaneously from various buses, consecutively or completely from a single bus. Even though, the power drained from several buses makes distribution system design and operation difficult. As a result of this, [22] proposed a bus selection strategy in which power is drawn from the bus with the maximum voltage level. The load may be able to change to alternative bus, but that dependent on the required condition. This topology is used for ship boat energy supply [23,24].

From the above discussion on structures of DC microgrid, it is obvious that each system configuration has its application. The reliability of the system changes with change in system structure. Table 1 presents the comparative analysis of different categories of microgrid structures.

3. Power flow analysis in DC microgrid

Direct-current (DC) power flow analysis is a crucial technique for understanding DC microgrids. It consists of passive elements, active sources, and nonlinear loads. These loads, which are usually constant power loads (CPLs), bring in hyperbolic non-convexities into the power flow modelling [25]. The measurement of voltage at each network node under steady-state conditions is the primary goal of power flow analysis. Notably, since the 1960 s, one of the subjects that has received the greatest attention is the power flow analysis of AC grids. In contrast, power flow analysis (PFA) in DC grids has only recently been investigated as a result of the resurrection of DC grids, which is being driven by advancements in power electronics, renewable production, and energy storage systems in the active networks paradigm [26]. In the past, specialist software such as Digsilent, Matpower, and ETAP was used to solve the DC PF because of its mathematical and computational complication. However, high purchase costs, complicated implementation, and processing times to solve the DC PF are issues with the specialist software. Due to these constraints, traditional solution approaches that don't require specialized software were developed in the last decade to address the PF in DC networks [27,28]. Furthermore, the non-convexities of the model render analytical solutions to power problems in DC resistive networks unfeasible. As a result, numerical methods are required to solve these problems [25].

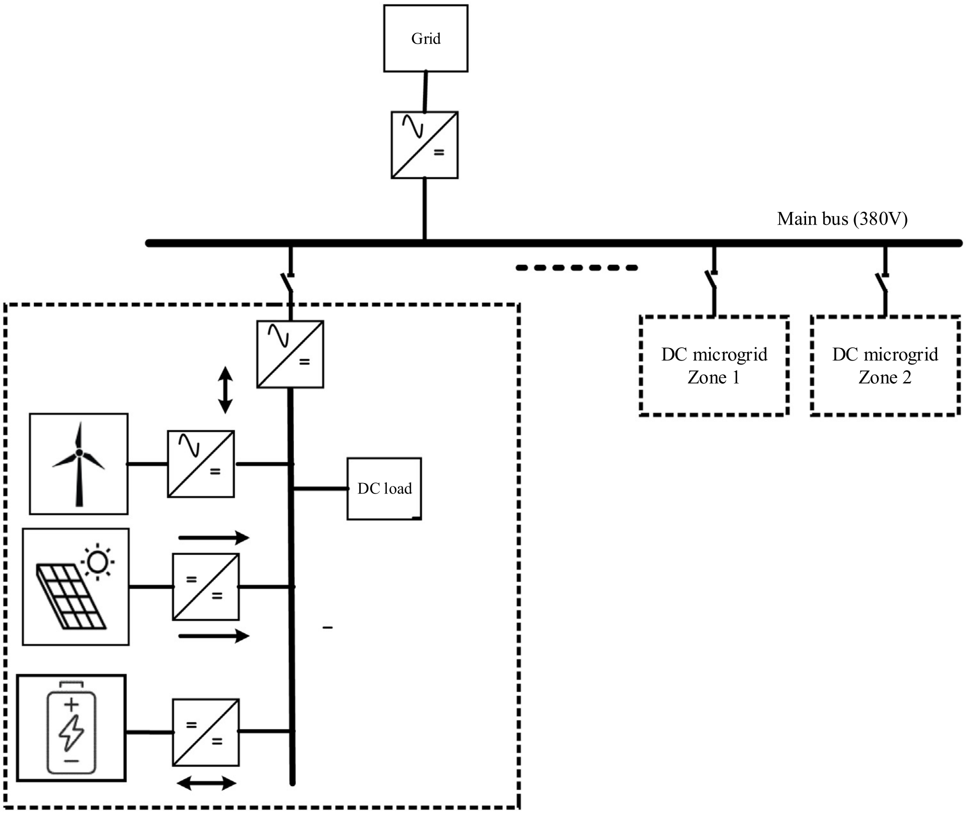

Fig. 9 Zonal topology.

Table 1 A comparison of different DC Microgrid topology [10,18].

DC microgrid (DCMG) Structure	Description	Pros	Cons	Inherent Stability	Voltage choice	ESS direct connection	Possibility of expanding to multiple buses	Reliability	Application
Radial topology	Enhances flexibility of operation and DC voltage regulation.	Increase reliability by improving vibrant stability and using many ESS.	Voltage and supply from ESS are uncontrollable.		12 V-48 V		×	High	Telecom system
Multi Bus topology	Several microgrids are linked in sequence and parallel to enhance efficiency and ability for power allocation.	Proper canalization of power among microgrid clusters.	A microgrid that abruptly shuts down can cause a fault in the system.	×	48 V-380 V	×		Average	LVDC, Interfaced AC Medium voltage
Multi Terminal topology	Many directions of energy flow increased reliability.	Flexible, reliable, and repetitive operation	Power flow is more complicated	×	380 V and above	×		High	Radial configuration in DCMG
Ring topology	In fault situation, restructured arrangement gives improved power flow	Two-way load connection approach to the common DC bus.	Weakness in voltage and power	×	24 V and above	×		High	DC distribution system
Ladder topology	Can connect to any of the buses to deliver bidirectional energy flow.	Scalability is high.	Structure difficult to design and control.	×	24 V and above	×		Very high	In an electric vehicle, a multi-input/multi-output converter is used.
Zonal topology	Different zones improve reliability, and each zone is energized by utility grid and distributed sources.	Better reliability by using additional switches, islanding minimizes error.	Appropriate DC voltage choice is required.	×	24 V and above	×		Average	AC distribution system.

3.1. Review of previous research on power flow analysis in DC microgrid topologies

For radial topologies, in [29], an approximated power flow and is suggested based on the Admittance Summation Technique. Furthermore, for DC microgrid, an iterative algorithm previously developed for AC microgrid has been adopted. The suggested techniques were evaluated and shown effective in comparison to the Newton-Raphson Technique in 33 and 144 nodes in meshed as well as 33 and 906 nodes in radial DC microgrids. The findings demonstrated that the approaches were created with good accuracy and achieved significant probabilistic power flow computation cost savings. The authors in[25] presented a novel iterative technique that is based on the upper triangular correlation between nodal and branch currents as well as simple impedance matrix to provides a quick analysis of the power flow problem for radial-configured DC networks with constant power loads (CPLs). When compared to conventional admittance-based approaches, this method's convergence can be enhanced in terms of the number of iterations and processing times needed by being able to avoid inverting non-diagonal matrices. In [30], the idea of equating the multi-bus system to a two bus radial system and evaluating the required constraints of the equivalent system is used to present a novel approach for assessing

Table 2 Overview of power flow analysis methods.

Ref.	Load flow techniques	Merits	Limitations
[38]	Newton-Downhill	■ Does not depend on the initial solution. ■ greater rate of convergence than Newton Rapson (NR).	■ order of convergence less than two. ■ if the Jacobian matrix is single, it fails.
[39]	Current Injection Method	■ Even under heavy load, there is good convergence. ■ less vulnerable to the R/X ratio.	■ If the PV DG number becomes too high, the system fails.
[40]	Back/Forward Branch Impedance Based	■ Does not require Jacobian matrix. ■ Linear back/forward sweep equations.	■ Disable for networks with meshing. ■ Excessive computation in large scale networks for a high PV DG number.
[41]	Backward/Forward Branch Current/Power Based	■ Does not require Jacobian matrix. ■ Does not depend on PV DG number.	■ Ineffective for large-scale networks with heavy loads.
[42]	Hybrid Super Position/ Gauss-Seidel	■ Does not require Jacobian matrix.	■ If the PV DG number becomes too high, the system fails.
[43]	Genetic Algorithm (GA) based power flow	■ easy to implement. ■ Reliable in convergence. ■ Suitable for offline problems.	■ Large scale networks have excessive computation time. ■ Sensitive to controller parameters of GA.
[44]	Particle swamp optimization (PSO)-based power flow	■ Reliable in convergence. ■ Suitable for offline problems. ■ Faster than GA.	■ Slower convergence than all the others except GA. ■ Large-scale networks have not been successful.
[45]	Artificial neural network (ANN) based power flow	■ It has the shortest computation time. ■ Appropriate for online problems.	■ restricted to a specified set of inputs. ■ Needy to the other techniques.
[46]	Probabilistic power flow analysis method	■ Critical uncertainties that have an impact on MG power flow are identified.	■ Computational cost is high. ■ Need to solve a system of nonlinear equations for different scenarios of microgrid operation.

voltage stability while taking economic criteria into account. A 203 bus WBSEB and a 6-bus system as a voltage stability indicator has been used for the implementation of the method. The authors in [31] proposed a power flow analysis based on a branch-and-bound search to discover the best switching status for transmission lines, while mixed-integer programming (MIP) relaxation is used to deal with non-convexities of power flows and converter loss equations. To get the optimal power flows inside the offshore network, an evolutionary technique known as covariance matrix adaptation (CMA) is presented in [32], To evaluate the effectiveness of the control approach in various case studies, the optimal power flow outcomes of the CMA algorithm are examined in a dynamic simulation model. A complex affine arithmetic-based alternating AC/DC power flow algorithm for the zonal MVDC shipboard power system in the presence of power variation is proposed in [33], to solve AC/DC power flows, a sequential method based on affine analysis is used. The suggested method can be used to design, plan, and operate MVDC power systems online when making decisions that are affected by power variation. The planning of an urban distribution network using a 2-step ladder architecture and taking joint nodes into account is presented in [34], a new network configuration using a mixed integer linear programming (MILP) method is adopted herein. The model includes conventional electrical limitations such power flow balance, line thermal limit, and number of consumers per feeder. Ladder circuit modelling of ungrounded DC rail traction system load flow numerical solution is proposed in [35], by successively obtaining the PFA of individual substations and wayside ladder circuits, it will be possible to efficiently compute the load flow and achieve numerical resilience for the entire dc traction system. In comparison to nodal voltage equations, the computing overhead of the proposed technique is linearly related to the number of substations. In [36], a power flow approach based on loop analysis theory and its linear formulation for DC microgrid is proposed. In this method, the branch powers, instead of the injected currents, are used to construct the suggested iterative approach and its linear approximation. When compared to the traditional Newton-Raphson approach and two other current linear methods for both radial and meshed networks, simulation results showed that the proposed methods were more accurate and faster. In [37], the power flow issue in low-voltage direct current (LVDC) power grids is reformulated for radial and mesh configuration using Taylor's series expansion. The suggested method avoids the usage of iterative approaches by offering an explicit solution to the system of power flow equations. In Table 2, the load flow techniques are highlighted with their merits and limitations.

4. Control strategy in DC microgrid

An effective control strategy should be employed for a DC microgrid system's well-organized operation and stability. Converters are critical components in the operation of DG micrgrids as they ensure proper load sharing and harmonized interconnections between different units of DC microgrid. In DC microgrid, various components are linked in parallel. Hence, voltage regulation that is flexible, precise current and power sharing between parallel-connected inverters ought to be all achieved. Control structure has become very important because of increased generation and loads that are not linear. Therefore, the objectives of the DC microgrid control are enumerated as follows [18,47,48]; Effective voltage and current control in grid linked and autonomous operation modes, comparative load balancing, steady operation with continuous power and loads that are not linear, synchronization amongst different distributed energy resources and energy storage devices, organization of DC microgrid and utility grid, DC microgrid power flow control, and network utility (if linked to the grid), in addition to smooth changeover from network connected to islanded mode.

DC microgrid control are characterized into two segments; Basic control strategy where the main element is communication and it is performed in the following different method namely, centralized, decentralised or distributed control as well as hybrid control, and the Multilevel strategy which is carried out via various control stages in a hierarchy. Fig. 10 shows the diagram of microgrid control structure.

4.1. Centralized control

In the centralized control scheme, a central regulator controls the distributed sources. The central controller compares the total generation and loads and then send load shedding signals to the loads that are not critical if the generation is not enough to power all the loads. The centralized controller can manage various energy sources in order to meet the demands of both critical loads and loads that are not critical [49,50]. This strategy offers strong supervision in the form of simple application, real-time system controllability, as well as observability. The distributed unit's data is being processed and returned via digital communication links. Communication is the prime mover in centralized control strategy. However, the centralized control strategy has limitations for example, the system's single point of failure, decreased flexibility, reliability, and scalability. Consequently, this category of control strategy is appropriate for DC microgrid on a small-scale application where the amount of data to be collected is limited [51,52]. The master–slave relationship is a common illustration of centralized control in which one of the converters serves as a master–slave, while the others serve as slaves. The master converter is static and operates as voltage mode regulator in a devoted master–slave, whereas the slave converters operate as current mode regulator [53,54]. Figs. 11 and 12 depict the architecture of centralized and master–slave control scheme respectively. A centralized power flow in a DC microgrid control technique connected with an EV was proposed by [55]. The operational mode of every agent in the DC microgrid was defined with respect to the information concerning the status of EV connection or disconnection, the first value of EV state of charge, wind power source, batteries SoC level and the availability of grid. [56] Presented a centralized robust controller in the case of an autonomous DC microgrid. The controller was designed to be resistant to the DG units' parameters uncertainties and to reduce exogenic instabilities. Control and management that is effective for a grid connected and autonomous DC microgrid was proposed by [57] to address a functional distribution system's voltage regulator and energy coordination. [58] suggested a robust controller for an islanded DC microgrid based on communication network delay where a steadying, robust and interpreter-based controller to ensure the time delay DC microgrid system's stability, it was designed using the Lyapunov-Krasovskii stability criterion. A cyber-attack detection and mitigation system for the control of distributed voltage of critical loads in DC microgrids was presented [59], for each DER here, a distributed voltage and current controllers were employed to perform the voltage regulation. A communication chart is used to share each DER

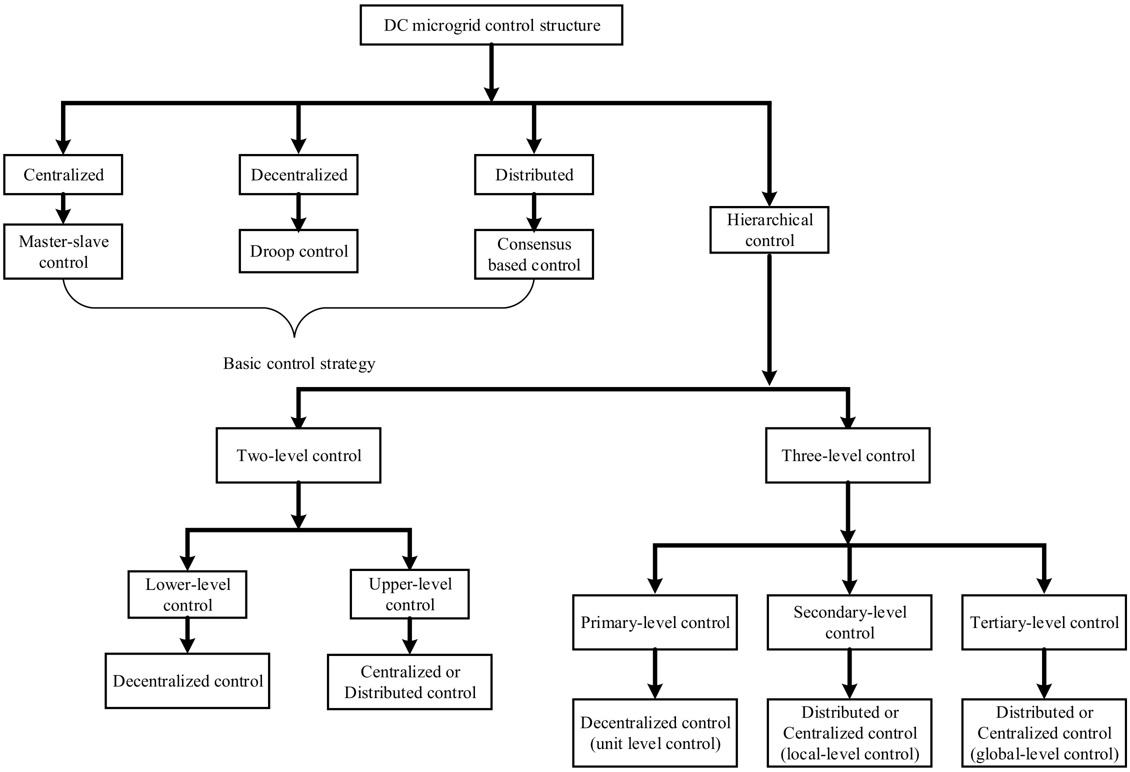

Fig. 10 DC microgrid control structure.

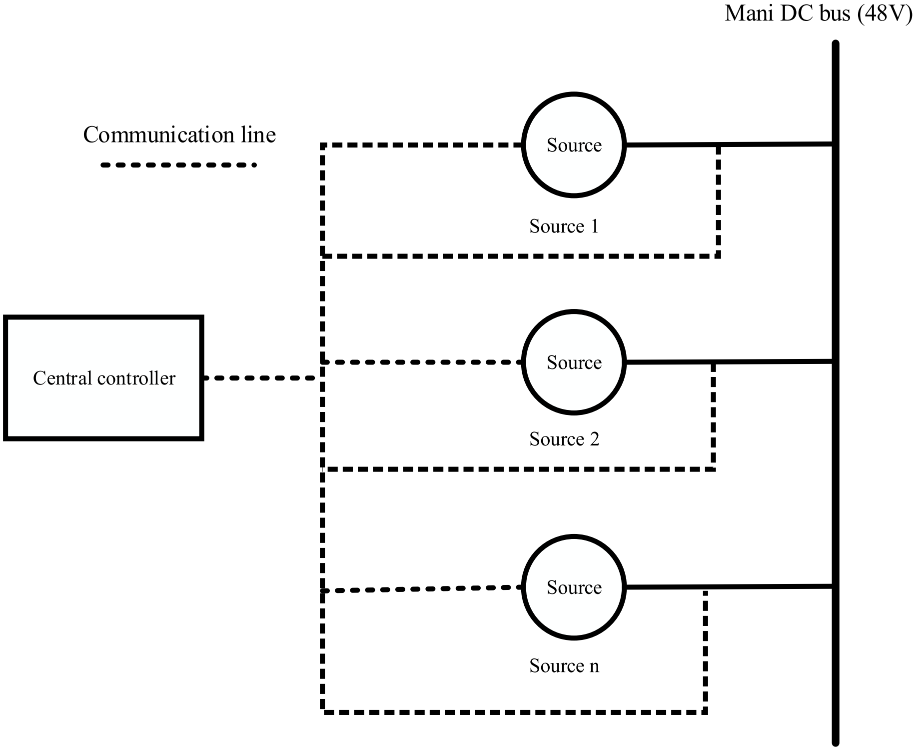

Fig. 11 Centralized control structure.

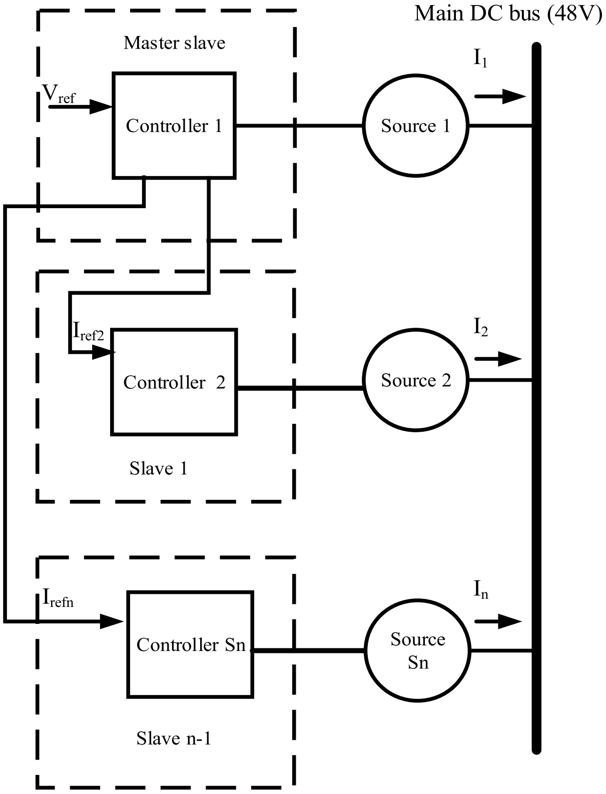

Fig. 12 Master slave control strategy.

current and voltage information. [60] also proposes a power flow control algorithm for centralized regulator in DC microgrids. The control algorithm guarantees DC bus voltage ripple compensation, MPPT, reduction of ES degradation and constraint for power interchange with the utility grid.

Fig. 13 shows a block diagram of a centralised control scheme proposed in [61]. The voltage V_{MG} at the point of common coupling (PCC) is regulated at its rated reference voltage V^{*}, the voltage at the PCC and the secondary level correction term δV communicate between the central unit and the local converters.

4.2. Decentralized control

Local controllers control the microgrid's connected converters in a decentralised control scheme. The input signal to the controllers are locally measured signals which are managed locally to produce gate pulses for converters. Fig. 14 depict a single line diagram of a decentralised control structure. Droop controllers are commonly used in decentralised control schemes. The droop control has been implemented to achieve decentralized control of each unit; however, it suffers from limitations such as the current sharing, system accuracy, and system stability which highly depends on the droop parameters [49,62,63]. For instance, high droop coefficient gives rise to a further damped system and increased precision in current sharing. Conversely, DC voltage deviation also increases with higher droop parameters. [64] proposes a vertical battery-centered droop control for effective power dispatch. Time-varying parameters of energy storage system (ESS) was used to calculate the droop controller's virtual resistance and reference voltage. [65] Proposed a decentralized control module-based plug and play (PnP) microgrid. In this control scheme, only local information is required for the control of each converter whereas SoC balancing, sharing of power and mode

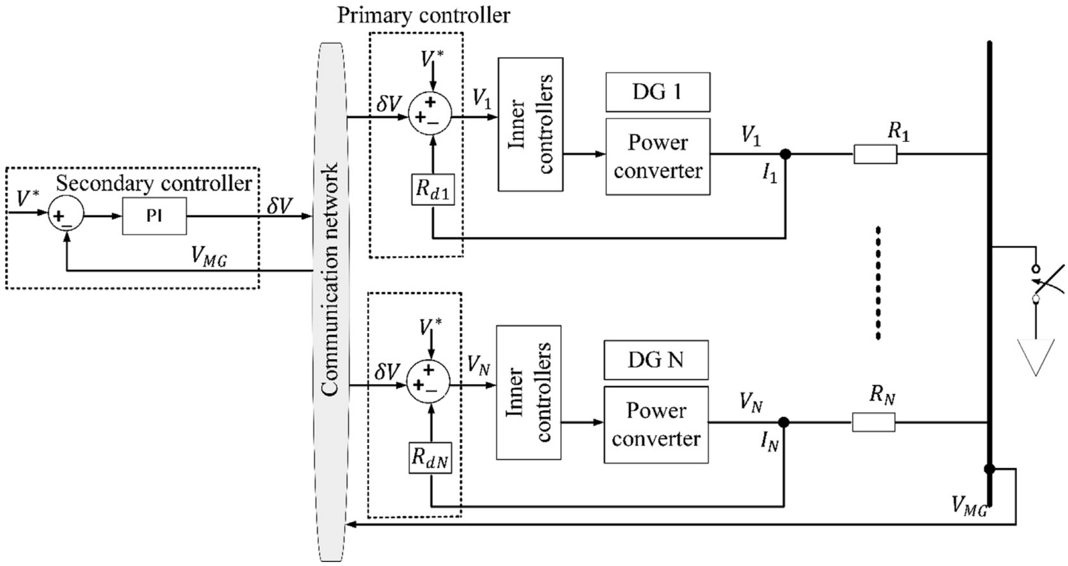

Fig. 13 Block diagram of a centralised control scheme.

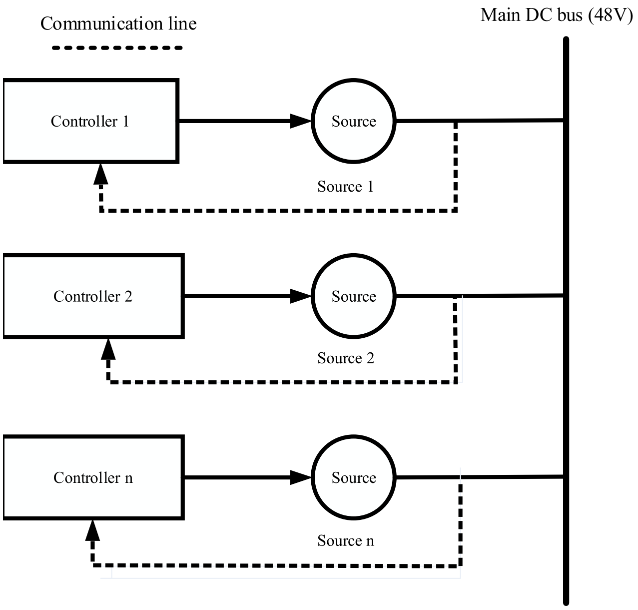

Fig. 14 Decentralized control structure.

acceptance can be accomplished concurrently without communication. [66] proposed a decentralised coordinated control strategy for PV, ESS, fuel cell, and HPU in a DC microgrid system. The battery control scheme took into account the SoC as well as the rapid charging and discharging power, droop control for PV MPPT mode, a PHU efficiency adaptive control scheme was developed, and the fuel cell was operated in constant power mode. [67] presented a decentralized droop control with filter in other to achieve state of charge matching in a DC microgrid by considering different SoC and capacities between battery energy storage (BES). A decentralized control strategy for a PV-BES management control to overcome voltage regulation control problems in the PV mode of dominance was proposed by [68]. With uncoupled control loops, even when the generation is dominant, the BES can still provide dynamic compensation. [69] suggested an even-triggered decentralized coordination control strategy in islanded electric-hydropower based DC microgrid by developing a better cost-effective control scheme based on the proposed structure's cost function making the energy storage system to carry out the matching scheme aimed at cost-effective and consistent operation. [70] proposed a control scheme for DC-DC converter parallel operation in a DC microgrid application. The technique combines droop control and an algorithm for instantaneous distribution of current to reduce current sharing inaccuracy. An artificial neural network based decentralized controller to identify and eliminate the attacks on current measurement using erroneous data injection was proposed by [71]. In each unit, a neural network was implemented to evaluate the DC current output of each converter, and a PI controller was used to eliminate the erroneous date injected from the attacked unit based on the assessed value. Fig. 15 shows a block diagram of a decentralized control scheme proposed in [72], The reference current (I_s) in the proposed control scheme regulate the duty circle of the converter and the reference current for the hysteresis current (I_{ref}) control is the output signal of the voltage droop control. The reference current and power of the i th power converter in the proposed scheme is expressed as

$$I_{ref,i} = G_i(s)\left[V^*_{o,i} - \left(\frac{w_{Lpf,i}}{s + w_{Lpf,i}}\right)V_{o,i}\right]\frac{V_{o,i}}{V_{s,i}} \tag{1}$$

$$\begin{cases} G_i(s) = \frac{1}{r_{d,i}}\left(1 + \frac{1}{sT_i}\right) \\ T_i = \frac{4}{w_{Lpf,i}}, \end{cases} \tag{2}$$

$$P_i = I_{ref,i}V_{o,i} \tag{3}$$

Where $G_i(s)$, T_i and $w_{Lpf,i}$ is the transfer function, integral constant, and cutoff frequency of the low pass filter respectively.

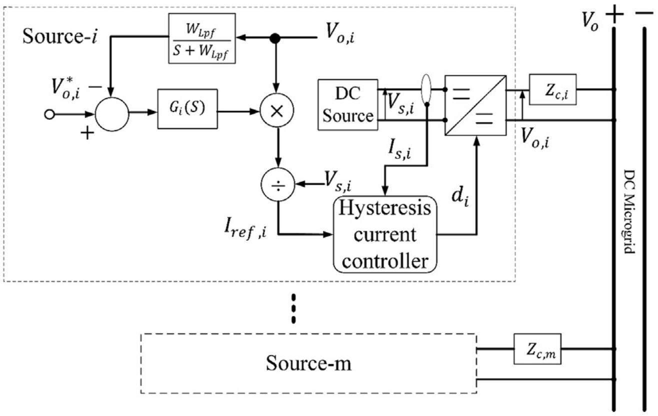

Fig. 15 Block diagram decentralized control structure.

4.3. Distributed control

This control scheme has features found in both central and decentralized control topologies, including an external communications link but no central controller. The distributed controllers communicate with one another via digital communication contacts, primarily a low bandwidth communication network or a power line communication network for exchanging data such as DG output current, bus voltage, and so on. Distribution control combines the advantage of both centralized and decentralized controller, Fig. 16 depicts a single line diagram of distributed control scheme, communication is limited to units that have access to a digital communication line (DCL). Local controller controls each unit that is connected to the microgrid. Each unit's controller exchanges information with its neighbors via the limited DCLs accessible. [73] has discussed the issue of network topology, robustness of network topology in the event of link failure, communication delay signals and the role of information interchange. [74] proposed an innovative method of distributed power control for converters interconnected in an autonomous power microgrid with objective of implementing power sharing between distributed generators and the interconnected converters. [75] developed a distributed controller for islanded microgrid which provides a data driven multi-agent framework for the regulation of voltage and current sharing. An even-triggered distributed secondary technique for radial DC microgrid is presented in [76] where converter can individually choose when to transmit a signal to its neighbor on a local basis. Bus voltage control and equal current distribution is accomplished. A unified hierarchical control method for power flow in autonomous DC microgrid collections was proposed in [77] and a distributed

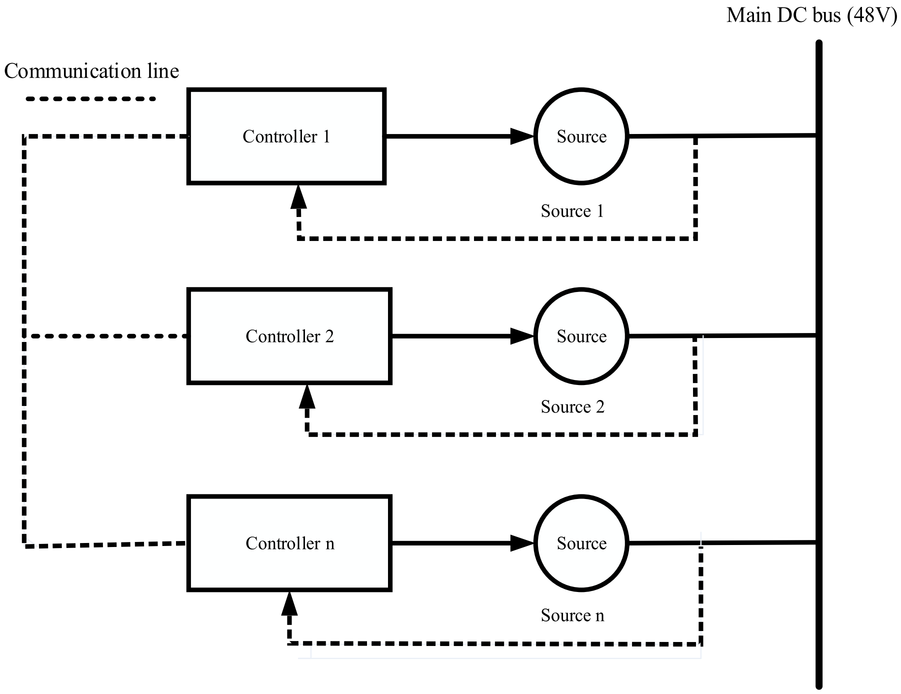

Fig. 16 Distributed control structure.

communication based unified hierarchical is employed to realize the objective. [78] proposed a distributed-based control method for voltage control and accurate sharing of current in DC-DC converters that are parallelly connected. The proposed controller does not depend on the number of active and load profile [79].

Fig. 17 shows a block diagram of a distributed control scheme proposed in [80]. The performance of the power converter is determined by the input current and output voltage signal of the power converter. The reference current signal in the proposed control scheme is given by the following equation

$$I_{ref,i} = G_i(s)\left[V_{ref,i} - G_{Lpf}V_{o,i}\right]\frac{V_{o,i}}{V_{s,i}} \tag{4}$$

$$\text{Where}\begin{cases} G_i(s) = \frac{1}{r_{d,i}}\left(1 + \frac{1}{sT_i}\right) \\ G_{Lpf} = \left(\frac{w_{Lpf}}{s + w_{Lpf}}\right) \\ T_i = \frac{4}{w_{Lpf}} \end{cases} \tag{5}$$

$$r_{d,i} \leq \frac{\Delta V_{o,max}}{i_{o,i}^{rated}} \tag{6}$$

Where $r_{d,i}$ is a droop gain, w_{Lpf} is cutoff frequently of low-pass filter, and $\Delta V_{o,max}$ is the maximum DC bus voltage deviation.

The summary of key outcomes in different control techniques is critically presented in Table 3. The symbols in columns three and four have adequate (+), moderate (+ +), and good (+ + +) denotation. Column five denotes complex (+), moderate (+ +), and simple (+ + +). The design complexity measure is concern with the mathematical models required for the control algorithm's implementation.

4.4. Hybrid decentralized and centralized control

Hybrid decentralized centralized control strategy is a form of multilevel method where a centralized and decentralized control methods are combined as depicted in Fig. 18. At the source level, a decentralized control approach is employed for instantaneous sharing of power making the central controller's function to become one that is centralised coordination rather than control of every connection in real time. With the integration of centralized control to the decentralized controller, it is possible to implement supply side control law. The main limitation in central control strategy is still maintained in hybrid central control because of the presence of communication line. Redundant communication lines and controllers needs to be provided in hybrid central control technique in other to improve the reliability of the system and doing so, will incur additional cost [99]. A hybrid central control strategy for charging of electric vehicle (EV) is proposed by [100] in which model predictive control along with adaptive charging method was employed to define close to ideal electric vehicles charging profiles instantaneously, while the decentralised controller coordinates the interaction among the electric vehicles as well as charging system controller. [101] suggested a hybrid central control method for residential power distribution to improve the voltage quality. Decentralized controllers maintain the voltage at the point of connection between the EVs and PV-wind system, then the energy storage is remotely controlled by central controller to further improve the voltage.

4.5. Hybrid distributed and decentralized control

This is a hybrid of distributed and decentralized control techniques, in which the control task is dispersed among the source controllers, as in distributed control. This type of control scheme has no external communication link; instead, the system power bus is used for communication among the source controllers. Therefore, decentralized controller efficiently controls each source by utilizing local variables. Fig. 19 depicts a typical hybrid distributed control structure. In a hybrid distributed and decentralized control strategy, the benefits of both control methods are combined. When there is communication

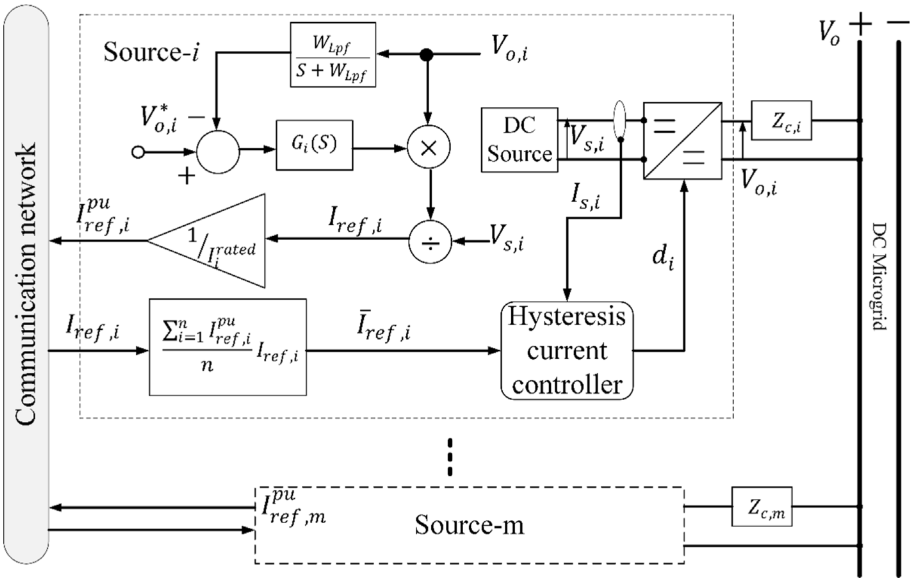

Fig. 17 Block diagram of distributed control scheme.

Table 3 Critical analysis in different control techniques.

Control structure	Technique	Current Sharing	Voltage control	Design complexity	Characteristics	Application
Centralized	Phase shift [81]	+ +	+ + +	+ +	More adaptable, Tolerant to faults	HVDC application
	PI Controller[82]	+ +	+ + +	+ + +	Robust, Improved efficiency but cannot handle nonlinearity	LVDC application
Decentralized	Conventional PI Controller[83]	+	+ + +	+ + +	Poor disturbance rejection and cannot handle nonlinearity	DC system
	Conventional droop control[84,85]	+ + +	+	+ + +	Deteriorate the proper power sharing performance by owing the effects of unequal line resistance.	LV microgrid
	Adaptive-Droop Strategy[86]	+ + +	+ +	+ +	Robust, Integrate RES such as SOFC, PVs and BESS	DC microgrid system
	Model predictive based control (MPC)[87,88]	+ + +	+	+	Requires accurate dynamic models with high computational cost and it suffers from lack of flexibility.	Microgrid system
	Sliding mode control [89,90]	+ + +	+ + +	+ +	Excellent robustness but chattering is high due to switching frequency.	DC system
	Nonlinear integral backsteppingSliding mode control[91]	+ +	+ + +	+	Reduced robustness	DC microgrid
	Second order sliding mode control[92]	+ + +	+ + +	+	Reduced robustness and chattering not eliminated	DC microgrid system
Distributed	DC bus signaling[93–95]	+	+	+ +	Deviations in voltage and current	DC microgrid
	Adaptive droop control [96]	+ + +	+	+ + +	The resistance between interconnected converter terminals should be known in advance, and weak convergence	LVDC microgrid grid
	Discrete time sliding mode control[97]	+ + +	+	+ +	Very weak robustness	DC microgrid grid
	PI Control with Adaptive Droop Control [98]	+ + +	+ +	+	Plug-and-Play compatibility, comparative load sharing	LVDC microgrid grid

line between the sources, it is possible to implement control law for the supply-side and the system being not dependent on the central controller as well as the external communication link has made it to retain the reliability advantage in decentralized control scheme. However, the limitations in distributed control method are still maintained in hybrid distributed control strategy. Hybrid distributed control employed in power line carrier (PLC) system based industrial control scheme to provide communication amongst control nodes [102]. Though, in other for modulation and demodulation of the control signal to occur, extra control hardware is needed at every node in the system. The use of power line as transmission intermediate has also created signal attenuation and limited bandwidth issues. Nevertheless, power line carriers can still be a reliable control scheme for small system if perhaps it is possible to solve these problems [103]. In order to accomplish accurate sharing of current and improve voltage restoration, a hybrid distributed and decentralized control strategy for a DC microgrid was proposed by [104]. Decentralized and distributed control strategies were implemented to accomplish enhanced voltage restoration along with precise power distribution respectively. This approach has shown to be robust in the presence of both communication delay and some communication failure scenarios. A hybrid distributed leader–follower control scheme for cascaded parallel microgrids is presented by [105], where one distributed generator act as a leather and the remaining distributed generators act as followers. Distributed control and decentralized control were employed to coordinate and control the leader and follower generators respectively. Improved voltage quality and synchronization of frequency were achieved with low communication bandwidth at low cost. [106] also recently suggested a hybrid distributed control scheme where local power converters connected in series are controlled by distributed controller and the decentralized controller handles the power sharing between parallelly arranged string with low communication bandwidth.

In summary, there is an improvement in the two hybrid control methods compared with the performance of individual control strategy. In hybrid centralized and decentralized control, for example, the advantage in centralized control is retained at a lower cost because the power sharing is done by the local decentralized controller. Likewise in hybrid dis-

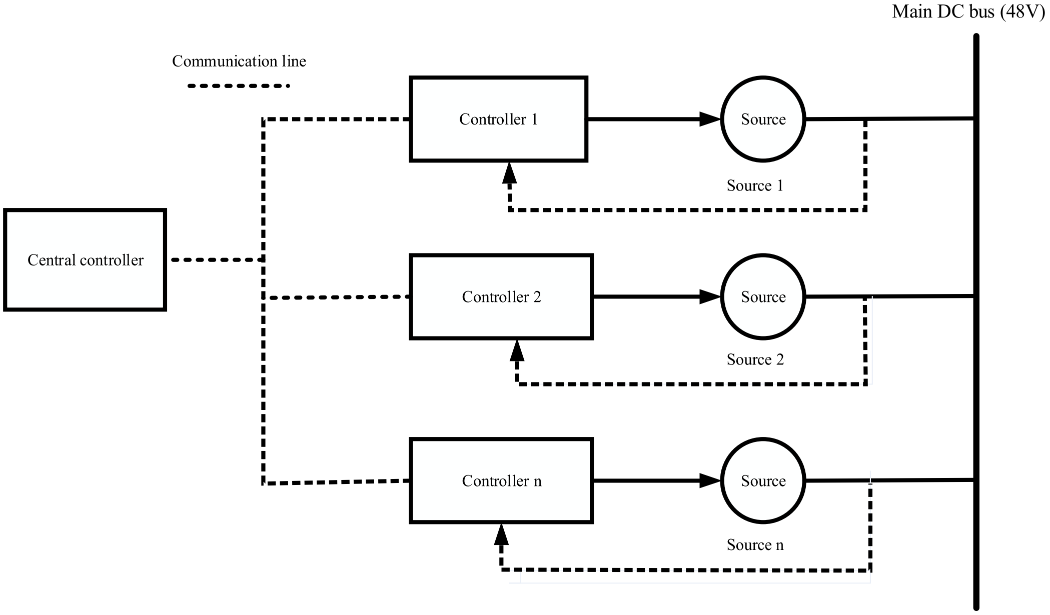

Fig. 18 Hybrid decentralized centralized control.

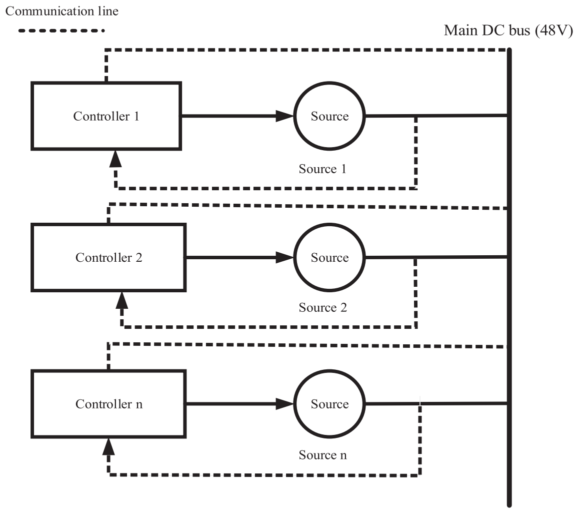

Fig. 19 Hybrid distributed centralized control.

tributed and decentralized control strategy, it has the advantage of distributed controller, no central controller or communication line. A comparative analysis of all the three basic control and the two hybrid control techniques is presented in Table 4.

Table 4 Summary of comparison between different control topologies.

Topology	Advantages	Disadvantages
Decentralized	No external communication line and controller, it is reliable and simple	Control law for supply side law cannot be implemented
Centralized	Potential to offer best performance	It cannot be implemented practically because real time central control of a large multi-input multi-output (MIMO) system necessitates far more computing power than is currently available.
Distributed	Enhanced reliability compared with central control	External communication line is needed
Hybrid decentralized and centralized	Offers similar performance as central controller at low cost	Dependency on central coordination and communication
Hybrid distributed and decentralized	Reliable and simple with no external controller or communication requirement	The size of a double direction line carrier system is limited, and there is possibility of transmission line impedance to corrupt the information

5. Hierarchical control structure

The modern power system which includes microgrids are very complex, and therefore, high intelligent control strategy is often required to accomplish the basic objectives like voltage, current, and power control, in addition, advanced control that includes sharing power among distributed generations, providing auxiliary services, reduced cost of operation, and partaking in energy market. Consequently, a centralized or any level decentralized control strategy cannot control the entire system. Microgrid hierarchical control consists primarily of three control stages: primary, secondary, and tertiary levels according to [93,107–119]. Hierarchical control as depicted in Fig. 20, is intended to control several energy storage devices (ESDs) and distributed generations, renewable energy resources and loads. The main local controller is the primary control. It uses local measurement to reestablish DC bus voltage and guarantee concurrent power sharing in both steady and dynamic states on the microgrid's lowest level. Primary control is faster and the voltage variation resulting from the primary controller is balanced by implementing secondary controller, which has a higher response time compared to the primary controller. Tertiary control is the highest level of control, which is characterized by slow response time. The operations of different units within the microgrid and grid utility is optimally maintained by the tertiary controller [120,121].

5.1. Primary control

Power electronic converters are essential components in DC microgrid that provides a controllable interface the sources and load. In a multi-level control system, the primary stage of control is the initial stage of control architecture and is in charge of voltage and current control. Inner loops for voltage and current control, as well as droop control for preliminary power sharing, comprise the primary control. DC bus signaling, fuzzy logic, master-level and Droop control is one of the most widely used primary level control strategies. The voltage operation range in DC bus signaling is divided into pre-specified sections, namely operation mode or voltage level. DC voltage is employed as a method of transmitting data in the DC bus signaling for power sharing between distributed generations in DC power system. DC bus signaling can achieve the independent control of each converter connected in parallel with a particular pre-indicated control rule. [122] uses DC bus signaling method to improve service reliability in DC microgrid by delivering a power supply to multiple possible loads not considered critical whilst ensuring uninterruptible power supply to loads that are considered critical. DC bus signaling is used in a power management scheme for an autonomous DC microgrid is reported by [95] where the DC bus voltage play a role as an information carrier between an interlink bidirectional converter and distributed generation controllers. [123] proposed a coordinated control method for a DC microgrid using DC bus signaling, an appropriate voltage requirement for a microgrid system is developed and then based on the real data acquired from meteorological agency through National Renewable Energy Lab (NREL), the correlation between wind and solar energy was evaluated. However, voltage variation is a major obstacle in DC bus signaling technique [49]. A fuzzy logic controller is proposed in [124] to regulate a bus voltage while maintaining power balance in a DC microgrid comprising of PV, fuel cell a battery bank. To find out the efficiency of the proposed method, the system has been validated under different unpredictable conditions such as 50 % changes in AC and DC loads, variation of irradiance and the function of the battery bank when a change is observed in fuel cell.

In the primary level of control, droop control is the most commonly used control strategy. It is preferred over the traditional techniques because it is a decentralized control and hence, it does not require any form of communication. Voltage-Current droop strategy is achieved by linearly minimizing the output voltage while output is maximized. This operating characteristic has made the droop technique suitable for primary control to accomplish the independent operation of converters connected in parallel and PnP capability particularly in the absence of communication [125,126]. However, this method is characterized with shortcomings such as voltage

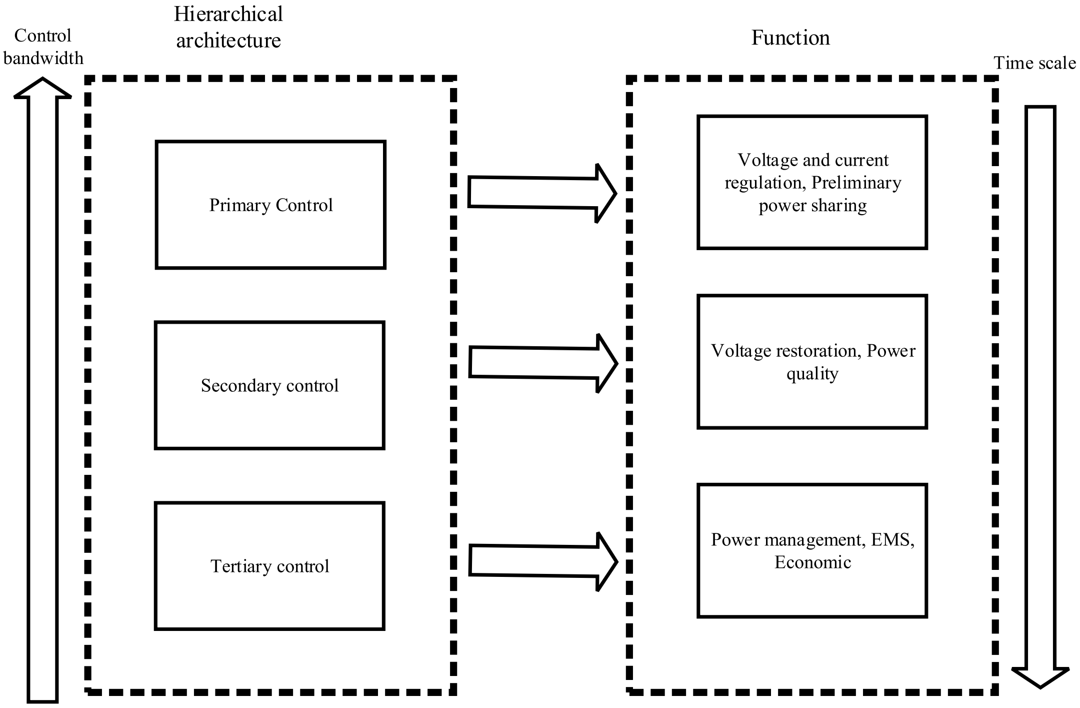

Fig. 20 Hierarchical control structure.

variation and inaccurate current sharing and as such, some researchers have suggested a nonlinear control to overcome these problems in [127–140]. A non-linear dynamic droop control is also suggested in [141] where power is distributed among battery and supercapacitor by employing dynamic droop gain. The method has outperformed the normal droop scheme. Fig. 21 shows the schematic diagram of primary drop control where the converters are arranged in parallel and share a common load with the aid of output virtual resistance (R_O). In the case of any voltage deviation, the output current will circulate among the two sources. Primary control technique is used to minimize the circulating current by employing virtual output resistance, (R_O). Reference voltage is altered by primary level control and sent to inner control loops through virtual output resistance.

5.2. Secondary control

This is another level of control in a multi-level control scheme that is accountable for the restoration of DC bus voltage deviation produced by the actions of droop control in the primary control level to a nominal value and power quality enhancement. Fig. 22 shows a block diagram of secondary control scheme presented in [9]. In the case of grid connected mode, it is also responsible for the microgrid and grid utility synchronization by ensuring that the distributed energy resources units within the microgrid are operated in an optimal and coordinated manner [142]. Secondary control act as a moderator between the tertiary and primary level which adjusts the mismatch between the set of values measured at primary level in microgrid and the values provided in tertiary level [114]. Secondary level control is employed to achieve a low cost of operation, reliable and a secured microgrid in both independent and grid connected mode of operation [143]. Microgrid central controller performs the conventional secondary stage control based on low communication bandwidth (LCB). The local controller receives a reference point for voltage and current from the secondary control. This improves the primary controller's output during current sharing. The secondary control layer can be classified into two categories according to [142,144,145] namely, centralised or distributed secondary controller which depends on local measurement and the centralized controller that depends on communication. In the case of centralized method, the DC link voltage is measured and regulated by a controller [113,146], but implementation of central voltage regulator requires communication link between the converters and the central controller and that affects the complete reliability and stability. To enhance the entire reliability and stability, a decentralized controller is employed in [147–150] because it is relatively less complicated and with no communication required as it operates local control task based on local measurement of individual converter. Distributed sec-

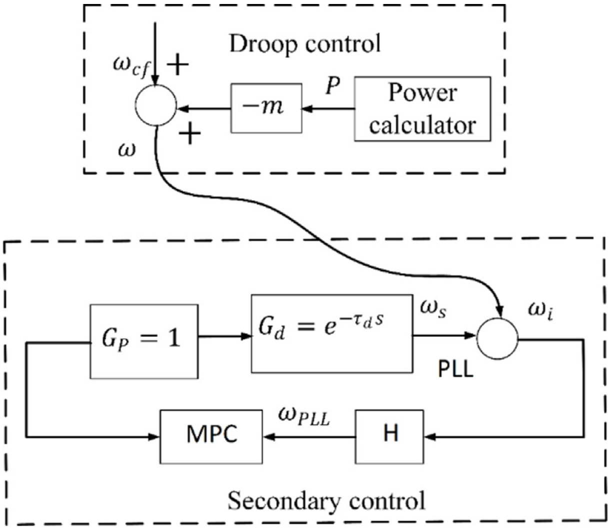

Fig. 22 Block diagram of secondary control scheme.

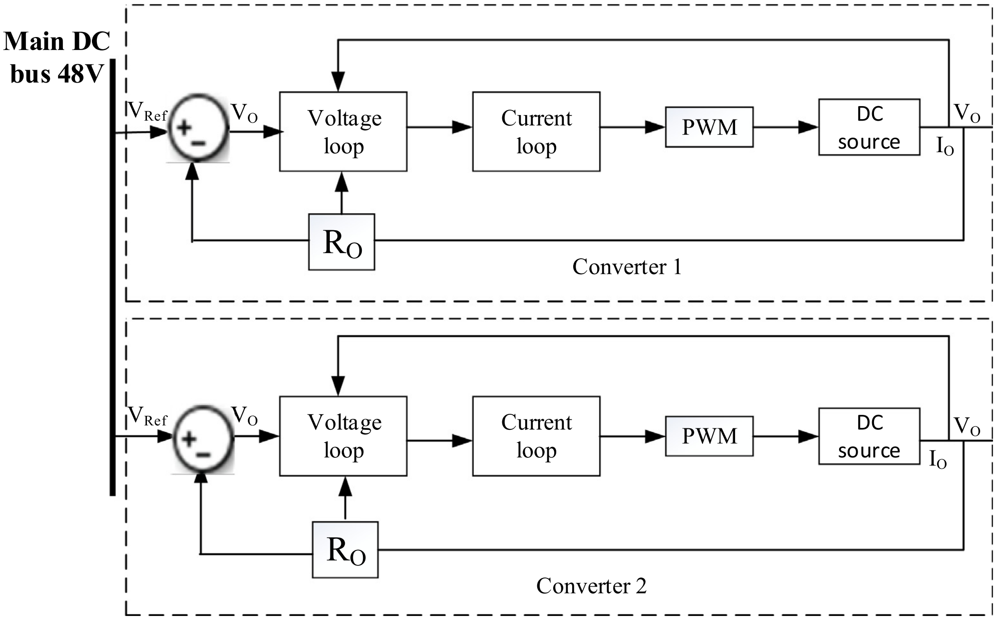

Fig. 21 DC microgrid primary control diagram.

ondary control does not require central controller and there is link of communication between neighboring converters. Distributed secondary approach is presented in [151–154]. It has the advantage of maintaining full functionality whenever there is failure in some communication lines, and it also overcome the problem of single point failure in centralized control approach [113].

5.3. Tertiary control

The tertiary control strategy is the highest and last hierarchical control level in microgrid that manages the power quality of the system and operate multiple microgrid connected with each DG unit of the system [111,155–157]. Fig. 23 depict a block diagram of a tertiary control scheme proposed in [61]. Even though the microgrid size is extremely small compared with conventional grid, It is necessary to have efficient economic dispatch and power flow which can be accomplished through the use of tertiary control approach [158,159]. Optimum operation of all microgrids is accomplished by employing tertiary control strategy. It can be implemented in centralized or decentralized approach too. Part of tertiary control strategy includes ensuring appropriate load management between the microgrid in a cluster, proper transfer of power between microgrids which allows for maximum use of renewable energy resources with high reliability and accessibility, communication, and operation [94,121]. Issues such as surplus production of power compared with the demand of microgrid, demand of microgrid with respect to voltage and frequency in the case of grid connected mode, the price at which the microgrid is ready to trade in the energy market and the issue of reserve (spinning and non-spinning) must be taken into consideration while evaluating microgrid economic status as a project [160]. Table 5 shows the comparative analysis between primary, secondary, and tertiary control strategy in hierarchical level [9,161,162].

5.3.1. Energy management system

In a broad sense, an energy management system (EMS) is a system that monitors and controls various aspects of energy-related systems such as measurement, operation, scheduling, and optimization. One of the most difficult tasks in microgrid application development is decreasing large energy differences caused by the uncertainties in power supply from the sporadic nature of renewable energy sources (RES) based distributed generations (DGs) and the dynamic nature of electricity utilization. The role of energy management system (EMS) in ensuring the stable operation of microgrid cannot be overemphasized. Maintaining a smooth operation within a microgrid, minimizing energy utilization, improving energy efficiency and end users' wellbeing are the principal objectives of EMS scheme [163]. An EMS must therefore be connected to each component of the system within a microgrid for control purposes, as shown in Fig. 24. EMS can be used in a variety of control technique such as the decentralized, centralized, distributed as well as multilevel control strategies. The control architecture and the adopted approach of solution of EMS determines the efficiency of EMS. Microgrid EMS performs many functions including forecasting of distributed energy resources power generation, consumption of load, analyzing, price of energy in the market, auxiliary market price and weather condition [164]. The integration of EMS in a building is essential as the control and optimization of energy usage is needed. The primary consumption and energy bills in a building can be minimized by applying real-time energy management. The application of intelligent energy management system in microgrid (both autonomous and grid connected mode) is also needed as it ensures optimal energy consumption and reduced cost [165]. The incorporation of renewable energy sources, as well as an energy storage system, EVs to grid with high power requirement of buildings and many more has made EMS to become more complex. However, machine learning and internet of things (IoT) are simultaneously increasing popularity and they are mutually very useful in the effective implementation of the EMS in the network [166]. Inappropriate coordination of microgrid integrated with EVs, RES, and ESS might cause the system to deviate from its expected performance. For instance, the charging and discharging of EVs in an uncoordinated approach could lead to thermal stress on the distribution network, likewise the integration of uncoordinated RES might cause reactive power problem [167]. EMS objective can be single or multiple, for example, it can be economic, technical, technoeconomic, environmental or social economic. Technical constraints are considered while establishing an economic objective, otherwise, the EMS optimization might deliver the best economic result, but the system

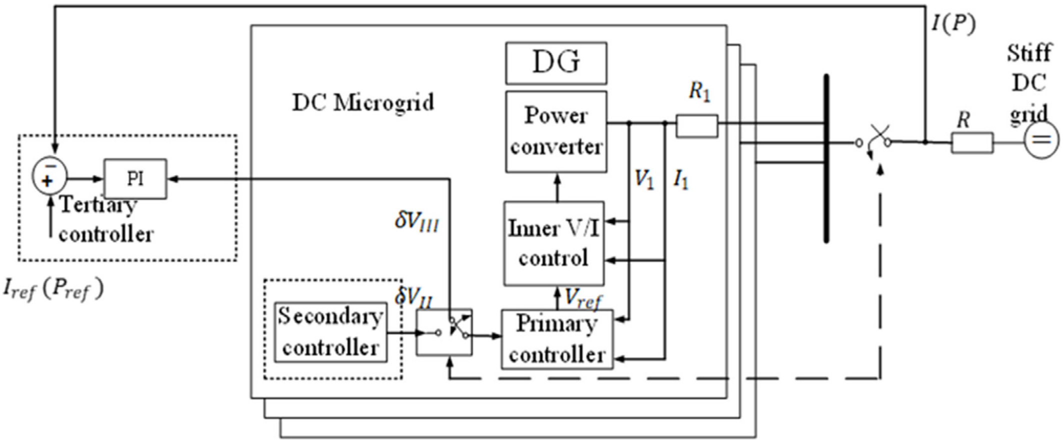

Fig. 23 Block diagram of tertiary control scheme.

Table 5 Microgrid control function by hierarchical layer.

Hierarchical layer	Time scale	Use of communication	Advantage	Disadvantage	Application
Primary control	Milliseconds-seconds	Absent	Because it is decentralized, it is preferred over other traditional methods.	Voltage variations and inaccuracies in current distribution	DC-DC converters
Secondary control	Seconds-minutes-one hour	Present	Global voltage regulation is provided, and voltage deviation is eliminated.	Single point of failure problem in centralised approach	Converters of all kinds
Tertiary control	Minutes-hours-days	Present	There are fewer power flow losses and operating costs.	Single point of failure problem in centralised approach	Power and energy management

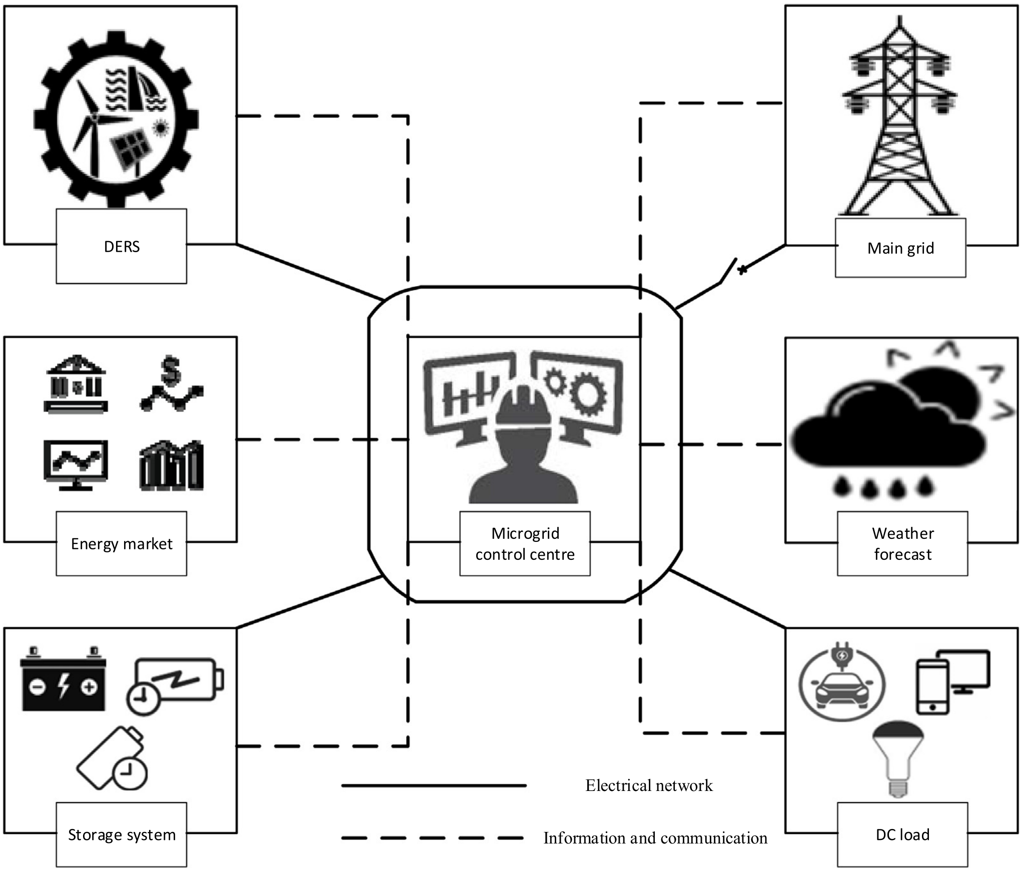

Fig. 24 DC-based microgrid EMS.

may be exposed to brownout, or damage the equipment operating under the distribution network. Environmental objectives with a view to reduce greenhouse gas emission (GHG) are set when several fossils fuel-based generation and RES are programmed to accomplish low carbon footstep generation. Social economic-based events are considered while economic events are influenced by the social development [168].

In the literature, several energy management techniques have been put out to ensure the most optimal and effective running of microgrids. Table 6 summarizes several research conducted in energy management system with different microgrid structures. As indicated in Fig. 25, there are two main types of commonly used approaches and procedures for the energy management of microgrid systems: classical techniques and artificial intelligence techniques.

The energy management of a DC-based microgrid has only been studied in a limited number of cases using classical techniques. The majority of research is geared toward optimizing the size of standalone hybrid renewable energy systems (HES). The next subsections provide an overview of certain frequently used classical approaches as outlined in Fig. 20 respectively.

Table 6 Critical analysis of EMSs based on classical and intelligent technique.

Reference	Optimization technique	Contributions	Limitation	Weaknesses	Single/ Multiple objective
[170]	Iterative algorithm	Novel learning-based and iterative IoT system for connected building BEM	large-scale grid-connected buildings and intelligent EV charging in cities	Renewable energy generation and ESS costs are not taken into account	Multiple
[172]	Linear programming	A heuristic algorithm based on linear programming for EVs charge and discharge	Not specified	High computational difficulty	Single
[185]	Linear and mixed integer linear programing	A novel' mix-mode' energy management strategy and method of sizing batteries for low cost microgrid operation	Battery Cost of generation	The optimization model did not consider battery degradation cost	Multiple
[174]	Hybrid Stochastic-Robust optimization	The improved HSR optimization method addresses renewable energy, load, and cost of electricity uncertainties	Power balance Renewable energy generation load	Complex mathematical formulation	Multiple
[186]	Stochastic	A simplified technique of integrating the effect of scheduling in autonomous mode on the grid-tied operation	Renewable power generation load Balance of power	Modelling of battery ageing is not considered The cost of DG's emission is not considered	Single
[176]	Stochastic model predictive control	A stochastic nonlinear model for a hybrid fuel cell-energy storage-cold ironing Ship that takes into account the effects of weather and resistance of wave uncertainty on the ship	The dynamics of FC and ESS operation at short time intervals	Batteries' charging and discharging rate were not taken into account Power loss not considered	Multiple
[187]	Model predictive control	The daily optimization that takes into account the batterie's deterioration due to corrosion and capacity losses	Not specified	Models using lithium batteries are excluded	Multiple
[188]	Fuzzy logic	The proposed strategy does not require complex model between the source power and converter output voltage to design the controller.	Energy storage not considered	The state of the battery and distributed sources are not specified	Single
[178]	Fuzzy logic	Easy implementation, enhanced the grid Quality power profile	Battery charge and discharge	The only controllable component is the battery charger and grid-tied converter Battery deterioration is not taken into account	Multiple
[189]	Artificial intelligent (Neural Network)	Reliable sensor less control and self-contained is implemented with less sensors without communication delay	Limited number of hidden layers	Nonlinear controller not considered	
[184]	Multi-agents	Automatically extract features, improved computing effectiveness and making it applicable to real-time application.	Modelling of the microgrid configuration in the energy management strategy not considered	Control scheme complex	Multiple
[190]	Multi-agent	An effective technique for managing energy storage in real-time to best account for power imbalance	Battery charge and discharge Power balance Load scheduling	Battery ageing prediction is not taken into account	Multiple
[191]	Multi-agent Bayesian reinforcement learning	Bayesian belief update which requires no direct communication and allow each agent to update itself on the activities of its peers in accordance with the Bayesian rule	Scalability of the algorithm	Complex formulation	Multiple

5.3.1.1. Energy management based on classical technique. Iterative algorithms are used in the literature to achieve various objective functions. In [169], an autonomous photovoltaic-wind turbine-fuel cell-battery storage-hydro turbine hybrid energy system (HES) was optimized using an iterative approach to reduce the system's overall energy cost for four different areas in Iran. In [170], an iterative algorithm and IoT-based application for self-scheduling energy storage sys-

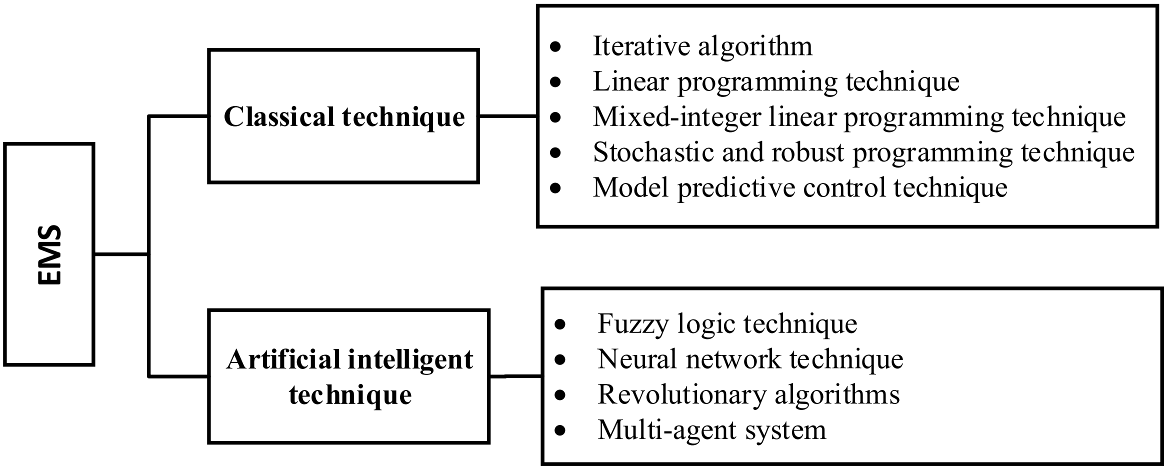

Fig. 25 Classification for energy management techniques.

tems (ESSs), thermal energy storage systems (TESSs), and connected building loads to maximize PV energy usage on-site, flatten the load profiles of buildings, and reduce electricity costs. Deep reinforcement learning (DRL) and a physics-based method were combined to first learn a good thermal storage policy and then use an iterative technique to generate the best control commands for all connected buildings' remaining loads. A rule-based-Iterative EMS has been proposed in this paper [171] for an autonomous photovoltaic-tidal turbine-diesel generator-battery storage microgrid in order to achieve the optimal PV-TT-Battery size while minimizing energy costs, greenhouse gas emissions costs, and losses in power due to static power converters. This paper [172] proposes a linear programming-based algorithm for charging and discharging electric vehicles. To deal with uncertain electric vehicle demand and departure times, as well as to evaluate the effect of smart charge and discharge scheduling of electric vehicles on peak load reduction in a building energy management system, an improved two-level heuristic algorithm was also developed. The authors in [173] proposes a mixed integer linear programming-based energy management system (EMS) for microgrid storage systems. The charging and discharging power of the battery is established in such a way that the overall cost of energy consumption is reduced, taking into account tariff variations in the power grid, renewable energy generation, as well as load requirement. The study then employs real-world data, and according to the simulation results, the proposed real-time approach outperforms the offline optimization approach, lowering operating costs by 3.3 percent. To take care of the intermittencies from renewable energy, uncertainty about load and electricity prices, the authors of [174] proposed a distributed stochastic-hybrid optimization method for smart grid energy management problems. The suggested a stochastic-robust hybrid approach combined the benefits of stochastic and robust strategies, resulting in an economic and robust solution with low computational difficulty because the stochastic scenarios were chosen efficiently and rationally. The proposed method outperformed the existing distributed algorithm developed in recent literature in terms of convergence speed. This paper [175] presented a hybrid stochastic-robust synchronized energy management strategy to improve MG's flexibility, reliability, and security indices. According to the simulation results, a well-coordinated optimum power management approach for local distributed generation (DGs), storage system (SS), and active loads in the MG improves network indices such as voltage profile, microgrid line, and station overloading. The authors of this paper [176] proposed a nonlinear model for optimum energy management of emission-free ships using hybrid fuel cell-energy storage system-cold ironing as sources while taking ageing factors of the fuel cell and storage system into account. The problem objectives are total operating costs, fuel cell and energy storage ageing factors. In addition, a stochastic model predictive control technique is tailored to the model in order to account for uncertainties in the course of optimization horizon. The simulation results demonstrate the proposed model's efficiency in meeting the ageing constraints of the fuel cell and energy storage system while minimizing operation costs.

5.3.1.2. Energy management based on artificial intelligent technique. Intelligent technologies like IoT and AI are being linked into renewable energy systems to develop them by making them more robust and responsive. All renewable energy (RE) systems are now using AI technologies. It has been demonstrated that the application of AI in RE systems has made technologies such as photovoltaic panels, wind turbines, and solar PV systems more affordable and efficient, increasing their use and perhaps displacing plants that burn fossil fuels [177]. A more thorough analysis of these research is provided in this paragraph. A fuzzy logic-based EMS for a grid-tied residential microgrid to obtain a smooth power profile is suggested in [178]. The suggested model reduces peaks and oscillations in the energy transfer to the primary grid. Additionally, it keeps the battery's SoC level at roughly 75 % of its maximum capacity to lengthen its lifespan. The authors in [179] suggested a straightforward and inexpensive control approach based on fuzzy logic PI controllers which are faster at recovering DC link voltage and more effective at employing supercapacitor for high charge -discharge circles, and hence reducing the batterie's stress and extending lifespan. An artificial intelligence (AI)-based approach was proposed by the authors of this research [180] as a way of achieving efficient microgrid EMS to reduce the whole cost of the microgrid, which includes fuel expenses, operating and maintenance costs, and generation unit emissions costs. To take DR into consideration, load is separated into four categories: critical load, controlled load, price-sensitive load, and thermal load. The suggested method is more effective than PSO at obtaining the greatest outcome. On the basis of forecasts from Model Predictive Control using Wavelet Neural Networks, the authors of this study [181] developed a novel energy management technique with focus on energy losses, unfulfilled load, and component resilience. Several wavelet neural networks make up the forecast models feeding the MPC, which are more appropriate for forecasts with limited spatial resolution. The simulations show that, in comparison to a rule base control, the strategy improves all indicators that are taken into account. [182] proposed a multi-agent system, incentive demand response, and a game theory-based energy trading model and solution algorithm for a microgrid cluster, microgrid, and user. Two level are involved for the optimization process, by developing an internal pricing enticement system, the microgrid cluster acts as a leader at the upper level and encourages the microgrid to take part in intra-cluster dispatching. The microgrid, acting as the follower, decides the quantity of power transactions based on the realized internal price in order to increase its own profits. The efficiency and good convergence of the suggested technique were confirmed by simulation results, which also showed that the suggested hierarchical game strategy can increase each participant's economic rewards, which is helpful for the development of a cooperative grid-connected microgrid cluster. Energy management system based on a multi-agent system for a DC microgrid is proposed in [183]. Here, a MAS with five major agents is employed, these agents primarily include a photovoltaic, solar, loads, and a server agent. The suggested system's operation is predicated on supplying loads as efficiently as possible using the available renewable sources. A multi-agent based energy management architecture for microgrid is presented in [184]. The goal is to reduce agent's energy losses, cost of operation. Each agent uses the proposed learning methodology and its own previous data to forecast the parameters and data it needs for scheduling. Table 6 present a critical summary the various optimization and management techniques applied in microgrid.

6. DC microgrid protection

Despite their numerous benefits, DC microgrids have been hampered by a complex protection challenge. The lack of natural zero crossing, stochastic nature of RES, and high probability of distributed energy (DE) outages exacerbate the task of fault detection and classification [192]. Furthermore, the rapid increase in DC fault current complicates the protection strategy and increases the size and capacity of the breaker. Lack of regulations and all-inclusiveness in standards for various voltage levels on grounding is also a significant impediment to its accelerated future. As a result, a dynamic protection model with adequate redundancy, selectivity, and sensitivity must be developed. However, some critical factors must be considered when designing this kind of protection model, namely: a) Improved converter sensitivity, particularly in faulty circumstances b) Modification of fault current (short-circuit current) under various mode of microgrid operation, c) Appropriate grounding system, d) a rapid upsurge in peak current thru a transient fault state, e) Arc fault analysis, and f) the issue of standardization [193]. The approaches related with Microgrid protection are summarized in brief as depicted in Fig. 26. These methods were gathered from literature reviews that were recently used to create microgrid protection techniques.

A novel protection scheme based on multi-sample differential protection scheme (MSD) to overcome the issue of instability as a result of time synchronization error with differential relays is proposed in [194], When taking into account latency limits from various measurement channels, the MSD technique achieves reliable internal fault detection while also ensuring stability for external fault conditions. A travelling wave based fault detection scheme is proposed in [195], high frequency components of DC fault current was cal-

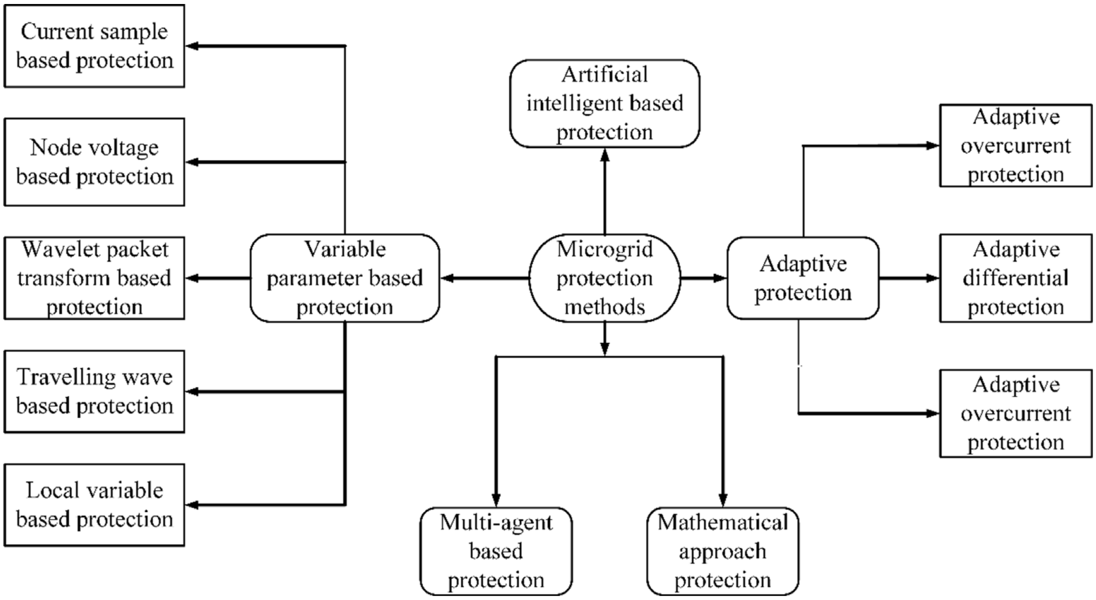

Fig. 26 Protection methods used for microgrid.

culated using the discrete wavelet form. The proposed technique can identify fault types and estimating fault locations. The authors in [196] proposed a protection scheme for detecting fault that uses a rate of change fault current and its moving average as discriminative feature. The scheme can detect fault within a few microseconds of their occurrence. A fast detection and location technique based on differential current for DC microgrid is proposed in [197], a modified cumulative sum average method is used to classify the fault type with the help of discrete frame differential current solution. The authors in [198] presented a novel learning based approach fault detection technique to improve detection accuracy and minimised unwanted false tripping in order to curtail the effect of DC arc faults through timely detection. This protection scheme enhances detection precision while decreasing the possibility of false trips. The authors in [199] presented a novel control and protection technique based on droop and current derivatives. The protection scheme can detect, characterize, and control fault current. Power sharing among converters is accomplished using droop, and then, an adaptive droop is used for fault current control. A protection scheme based on convolution neural network is proposed by [192], The technique reduces the difficulty and cost of the feature extraction procedure. The convolutional neural network classifier appropriately separates between all incidents, and its implementation is verified by a variety of metrics.

Table 7 summarizes the findings of a review of dc microgrid protection schemes. The methods used to create protection schemes along with their advantages and shortcomings are presented.

7. Challenges and recommendations on DC microgrid

DC microgrid has many technical advantages over AC microgrid, these include easy integration of renewable energy resources, direct connection between the consumer loads and DC bus voltage, more simply mitigated harmonics, and no frequency as well as reactive power control problem. On the other hand, the DC microgrid also has its downside such as complex controller, SoC and power imbalances, planning and operation difficulty, high fault current because of short circuit, and coupled with uncertainties because of intermittent characteristics of wind and solar irradiance. Therefore, in other to maintain stability, reliability, and flexibility of the DC microgrid, the system planners and operators must be careful in planning

Table 7 Overview of DC microgrid protection schemes.

Refs.	Developed techniques	Strengths	Weakness
[200]	Inductance estimation-based scheme	■ Changes in microgrid topology have no effect. ■ Used local measurement data only.	■ No consideration is given to the communication system.
[194]	Percentage differential current technique	■ Very fast response ■ When current transformer is saturated, the system does not malfunction.	■ Centralized protection approach, it is prone to single point failure. ■ Increase in losses due to various power converters.
[201]	Intelligent fault detection-based scheme	■ Improved accuracy (95.7 %). ■ Reduced implementation costs.	■ Considered only low impedance faults. ■ The strategy does not address instability of microgrid
[202]	Differential current-based fault detection approach	■ Greater precision in calculating fault distance. ■ Quick response ■ Noniterative technique is used to calculate the distance of the fault	■ The most terrible scenario occurs during a DC arc fault condition when proper grounding is not present.
[203]	Dijkstra Algorithm with Prims for Adaptive Protection	■ determining the precise type of fault and its position. ■ Microgrid is constantly monitored.	■ A large bus system is not taken into account here.
[204]	Deep recurrent neural network technique	■ PV system anomaly detection, increased system efficacy, and reduced maintenance	■ An error-free environment is required for training the data on its normal behaviour. ■ Faulty condition not conspired for experiment.
[205]	DC microgrid protection schemes based on blockchain	■ Microgrid is protected against communication failure and cyber-attacks.	■ The detection time for cyber-attacks is less than 2.5 ms, there is need for improvement.
[206]	Decentralised cuckoo artificial neural network-based protection technique.	■ The protection technique offers backup protection. ■ It has over 96 % precision and 99 % reliability.	■ Each classifier in the Artificial Neural Network can detect faults using only local voltage and current measurements.
[207]	Master slave-virtual inertia microgrid protection scheme	■ Improve the shortcomings of converter-based distributed generator systems due to a lack of inertia. ■ Improving controlled voltage steady-state and transient responses in microgrids	■ Considered voltage and reactive power control only.
[208]	voltage-based power differential protection technique	■ Precise and effective detection and identification of faults. ■ Can be implemented in both radial and mesh configuration.	■ System voltage can only be used for measurement. ■ A relay is required for each node.

and operating DC microgrid. Consequently, innovative planning and operation strategy, effective DC bus voltage control, improved current and power sharing techniques have been developed and perhaps employed to take care of these problems. However, there is still possibility of developing a better planning, operation, and control techniques by conducting extensive research in the following directions as summarized; [79,209,210];

i. Proper modeling of a system is needed for an effective planning and operation of DC microgrid. Therefore, an improved or innovative model should be developed considering the intermittent nature of DGs in microgrid in other to minimize the planning and operation cost.
ii. Several innovative robust, simple, cost effective and optimal control strategies can be developed or improved with view to achieve a proper voltage regulation and accurate current sharing.
iii. High level RES integration DC comes with reduced inertia of the overall DC microgrid which degrade the performance of the voltage control. Even though some control techniques have been developed to handle this issue, but more work is still required in this aspect since DC microgrid is becoming 100 % RES based system.
iv. Microgrid control should be able to operate the system in optimum condition always. For instance, harnessing of maximum renewable energy, to use energy storage device optimally and keeping the DC bus voltage within limits.
v. Cost effective, less complex, and viable communication techniques for the control of microgrid operation should be used in remote location.
vi. Control scheme for batteries should also meet the extreme of over charge and undercharge when charging and discharging correspondingly in view of minimization of recurrent charge and discharge micro-cycles because of slight change in generation or loads.
vii. More work should also conduct regarding the life-span enhancement of storage devices whilst maintaining power stability and re-establishing DC bus voltage.
viii. Keeping the grid-connected and islanded systems stable, as well as ensuring seamless transfer between the two systems through coordinated and local controls
ix. An optimal grounding that reduces the DC stray current and maximizes the personal security
x. Another challenge is the cost-effective design of circuit breakers due to non-zero crossing of DC current.

8. Discussions

Several papers on DC microgrid control have been reviewed in this study. The structure of DC microgrid, control methods, energy management as well as DC microgrid challenges are discussed.

DC microgrid architecture with their application, advantage and disadvantage are discussed. The DC microgrid topology is classified into six categories: Radial bus topology, Multi bus topology, Multi terminal bus topology, Ladder bus topology, Ring bus topology and Zonal type bus topology. The DC microgrid structure is a function of the following factors: robustness, controllability, economic rate of the system, utilization of the resources, the weather and flexibility to the end users. All the DC microgrid structures have their specific application each with advantage and disadvantage. Further research is required to overcome the limitations and develop a standard architecture for DC microgrid.

Several control techniques each with their objectives have been explained. The overall control topology is divided into two categories: the basic control strategy and the multilevel or hierarchical control strategy. The basic control strategy is further classified based on communication links namely: decentralized, centralized, distributed as well as hybrid decentralized centralized, and distributed decentralized topologies. In decentralized control strategy, the input signal to the controller is locally measured signals which are locally processed to generate gate pulse for the converters. The most common method used in decentralized control strategy droop control. However, in droop control method, there is trade-off between current sharing accuracy and voltage deviation as high droop gain increases current sharing accuracy and voltage deviation increases at the same time. Communication is the heartbeat of centralized control strategy. There is a communication link between the controllers in the neighboring converter and the central controller. The central controller compares the total generation and the load and then send load shading signal to the non-critical loads in the case of insufficient generation to supply the loads. It provides strong supervision which includes system real-time controllability and observability. Although, the centralized control method suffers from the limitation of single point failure. Distributed controllers are linked to each other via a digital communication channel in distributed control strategy. It combines both advantage of decentralized and centralized control strategy. Multilevel control with all the control levels have been explained in this paper. Primary controller which is the fastest compared to secondary and tertiary is implemented in the first control level, secondary controller balances the voltage deviation resulting from the primary control and the top-level control layer which is tertiary control manage the operations of various units within the microgrid and the grid utility. EMS as part of tertiary control is discussed. Maintaining an energy balance between the intermittent DGs and the stochastic nature of the electricity demand is a major issue in microgrid operation. But luckily enough, the advancement in internet of things (IoT) or rather, information and communication technology has made it possible to develop various energy management approaches that ensures balance of power between DGs through utility or local microgrid and the demand side. However, there is need for the research community to work on how to thoroughly assess the potential benefits and costs of microgrid energy management.

Finally, DC microgrid has many technical advantages over AC microgrid, which include easy integration of renewable energy resources, direct connection between the consumer loads and DC bus voltage, more simply mitigated harmonics, and no frequency as well as reactive power control problem. However, DC microgrid also has its own shortcoming such as complex controller, SoC and power imbalances, high fault current because of short circuit, high uncertainties because of intermittent characteristics of wind speed and solar irradiance are all noticed in a DC microgrid. Groundbreaking research on DC microgrid control strategy can remove these drawbacks.

9. Conclusions

This scientific article presents a painstaking review of DC microgrid control. In terms of reliability, efficiency, power quality and perhaps cost, DC microgrid is superior and promising compared with AC or hybrid microgrid system. However, the advancement in power electronic technology development and the rapidly growing deployment of distributed generations (DGs) is accompanied with technical issues such as the effective control and management of the microgrid operation. Therefore, extensive research on the aspect of DC microgrid control, standards, and management system are required. The fundamental control structures namely, centralized, decentralized, distributed, and multilevel, that is, hierarchical control layers have been critically reviewed along with energy management system of DC microgrid. Challenges of DC microgrid with feature recommendations have been presented. This review article concluded that further research on control techniques, a standard architecture for DC microgrid, and balance of power between distributed generations (DGs) and the dynamic load demand would be an extraordinary contribution toward realizing a matured DC microgrid technology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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