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A brief review on the application of droop control methods for voltage source converters in direct current microgrid

Ghazanfar Shahgholian[1,2,*], Mohammadreza Moradian[1,2], Mohammad Amin Honarvar[1,2]

[1] *Department of Electrical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran.*
[2] *Smart Microgrid Research Center, Najafabad Branch, Islamic Azad University, Najafabad, Iran.*

[*] **Corresponding author:** shahgholian@iaun.ac.ir

Original Research

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Abstract:

The microgrid acts as a single controllable system, and by generating flexible power, it ensures the reliability of the electric grid. The use of microgrid helps to solve environmental pollution problems. The microgrid control operation is different from the grid-connected mode. Based on the nature of bus voltage, microgrids are divided into two categories: DC microgrid and AC microgrid. Several studies have been conducted in the field of microgrid application and exploitation, but their expansion still faces various challenges. DC microgrids are more reliable than ac microgrids. The purpose of this article is to review the documentation and provide a short review on the application of the droop method to control parallel converters in direct current microgrids. Droop control method is a popular and well-known technique for sharing load power, which is widely used in DC microgrids. In this control strategy, the reference voltage of each source is determined based on the nominal output voltage, output current and loss factor, where the power sharing rate is determined by increasing the loss. The various advantages of direct current microgrids will cause them to be used more in the near future, so this review is for researchers as a preliminary research to study the development of direct current microgrids based on the application of droop control methods. And improving it can be useful.

Keywords: Droop strategy; Microgrid; Parallel converters control; Renewable energy

1. Introduction

Energy is a fundamental need for continued economic development, social welfare, improvement of quality of life and security of society. One of the important issues is the wide range of human needs for energy resources, so that the effort to achieve permanent energy sources is considered one of the long-standing goals of man [1, 2]. Over the years, energy resources have been considered one of the most important factors in the economic, industrial and scientific life of countries, and national security and the sustainability of government systems also depend to a large extent on access to energy resources. The world's need for energy has increased significantly in recent years, and fossil energy resources do not meet this need for future evolution and development [3, 4].

Renewable energy is a type of energy whose source of production, unlike non-renewable energy, can be renewed by nature in a short period of time. Given that renewable energy sources are available in all parts of the world, and unlike fossil fuels, they do not have access restrictions, the role of new energies is well known, while fossil fuel sources are not only found only in certain countries, but also face increasing prices [5, 6].

The global need for energy has surged significantly in the last decade, and fossil energy sources are insufficient to satisfy future evolutionary and developmental requirements [7, 8]. With the development of the industry and the increase in consumer demand and environmental issues, the penetration of scattered production sources and energy production from them in the power system has increased greatly [9, 10]. Various technical, economic and environmental factors have caused the expansion of distributed energy production in power systems [11, 12]. Direct connection of renewable energy resources such as solar photovoltaic, fuel cell, water energy and wind energy to the main grid causes problems in voltage and frequency and also protection systems [13, 14]. Microgrids have been widely considered in studies as a possible approach for integrating distributed energy sources with energy storage systems in the electrical grid. The increasing use of renewable energy sources requires advanced energy management in microgrid systems for their sustainability, efficiency, and reliability [15, 16]. The intermittent nature of renewable energy sources makes their integration into a smart grid more difficult compared to traditional power plants with relatively constant energy production [17, 18]. At present, microgrids supply a small percentage of energy, but in the near future they will supply a significant amount of energy [19, 20].

The high use of renewable energy resources like photovoltaic arrays and wind turbines has expanded the use of microgrids [21, 22]. Microgrid is a decentralized network and a self-sufficient energy system, which reduces the adverse effects of distributed generation. It also saves money in long-distance transmission, and improves power efficiency by reducing transmission power losses. The additional capacity provided by microgrids is used to prevent overload situations and blackout of the national network [23, 24]. In short, the advantages of microgrids include increasing security and energy efficiency, improving service quality and electrical reliability, minimizing overall energy consumption, improving power quality and positive environmental effects [25, 26]. Also, the microgrid has a faster demand response than the traditional power system [27, 28]. There are some challenging problems to achieve and ensure the benefits of microgrids. Among the disadvantages of microgrids and the main obstacle to the widespread deployment of their technology, we can mention high initial cost, complexity, compliance with specific regulations, design on a limited scale, lack of necessary standards, and technical problems. Another disadvantage is the irregular injection of power due to variable renewable energy sources. Also, the microgrid needs an energy storage system [29, 30].

1.1 Research highlights

Microgrids have been widely considered in studies as a possible approach to integrate distributed energy sources with energy storage systems in the electrical grid. Many studies so far in various fields such as protection [31, 32], power sharing [33, 34], energy management [35, 36], control [37, 38], power quality [39, 40], load sharing [41], modeling [42, 43], stability [44, 45] and optimization [46, 47] has been done for direct current microgrids.

Also, review studies have been published in various fields of application of direct current microgrids and related challenges, some of which are mentioned in Table 1. The above review shows that there are still huge challenges in the study of microgrids considering the variable and random characteristics of renewable energies.

Droop control is effectively employed to control microgrids in both grid-tied and stand-alone operating conditions. In this paper, the aim is to study the performance and application of the droop regulation method in direct current (dc) microgrids. The main highlights of this review can be illustrated as follows:

- Classification of microgrids based on the distribution system and stating the advantages and disadvantages of DC microgrids.
- Presenting a number of simulation results in the field of application of droop regulation method in DC microgrid.
- Discussing and investigating the classification of microgrid control methods based on control modes.
- Discussion and investigation of droop techniques in microgrid control design.
- Distribution of droop control in direct current microgrid.

1.2 Paper structure and research method

The main aim of this article is to evaluate the current status of studies conducted in the field of application of droop strategy in direct current microgrids and to identify related issues. The structure of the article is arranged in 6 sections. After pointing out the importance of the subject and stating the problem in this section, in section 2, the structure of the direct current microgrid with its advantages and disadvantages is mentioned. Microgrid control methods are an important field of study and application, which is mentioned in section 3. In section 4, the droop strategy in the parallel connection of converters in the microgrid based on the DC microgrid is stated. In section 5, a number of studies and simulation results of droop control in DC microgrids are given. Finally, the conclusions and suggestions are stated in section 6.

2. Direct current microgrid structure

In recent years, energy has become an important and influential factor in the expansion and creation of various industries, and therefore has great importance in the industrial sector [57, 58]. Microgrids are classified based on various factors. Based on the system architecture and voltage characteristics, microgrids are divided into direct current [59, 60], alternating current [61, 62] and hybrid [63, 64]. Based on the line parameters, microgrids are usually considered as inductive or resistive systems, so that the line parameters affect the control of the microgrid and the selection of the controller type. The inductive part of the line in medium and high voltage networks is usually larger than the resistive part of the line impedance [65, 66]. The impedance in low voltage networks is essentially resistance and the inductive part of the impedance is negligible and can be neglected. In terms of the control loops required in the microgrid, the control levels are divided into primary control, secondary control, tertiary control [67, 68]. Based on the control architecture criterion or any monitoring problem, there are two different approaches: centralized control and decentralized control. Based on the operation, microgrids are divided into grid-independent and grid-connected. In autonomous microgrids, decentralized control methods are often used

Table 1. A number of review studies in the field of microgrids.

Subject	Ref.	The highlight and result of the research
Control	[48]	Hierarchical control strategies in a dc microgrid are investigated. Hierarchical control strategy is divided into three primary, secondary and tertiary layers based on their performance. Different control methods for current and voltage regulation at the first level, power sharing and voltage error correction at the second level and energy management for minimum power loss reduction at the third level have been investigated.
	[49]	High power quality along with cost reduction and control simplicity are the advantages of dc microgrid. The classification of different primary and secondary control techniques for dc microgrids has been investigated. Load sharing mechanisms used in primary control are shown for active methods and passive methods. The classification of different methods for second level control is also mentioned.
	[50]	To implement dc microgrids, a stable control strategy is needed. Voltage control strategy in dc microgrid is investigated. By combining two centralized and decentralized control methods, their advantages have been used for the control accuracy and reliability of the power grid, and it can be an effective help in the development of DC microgrids.
Protection	[51]	Protection is one of the challenges of expanding the use of direct current microgrids, and creating a suitable protection plan is one of the problems of protecting the grid. In this study, the problems and protection schemes of direct current grids in modern power systems have been analyzed and investigated. Protection methods for direct current microgrid have been compared and different methods for solving protection problems have been discussed.
	[52]	The challenges of protecting the direct current microgrid system have undermined its booming benefits. The nature of the fault current and the time change of the microgrid architecture have an effect on the protection plan. In this study, direct current microgrid protection techniques with protection requirements have been investigated.
Energy management	[53]	Renewable energy sources have been used to meet the energy demand in the power system. Direct current microgrids have high performance and good reliability, but they are still weak in terms of network architecture and control system. In this study, various methods and strategies related to energy management in microgrid have been investigated. The energy management system has been considered in terms of cost and optimization in direct current microgrids.
	[54]	Exploiting the potential of microgrids in smart grids with renewable energy will be accompanied by various challenges. The development of direct current microgrids and various challenges such as power quality and operation, appropriate control and energy management strategies are reviewed in this study. Energy control and management strategies have a great impact on other microgrid performance indicators such as operating cost and greenhouse gas emissions.

Continued of Table 1.

Subject	Ref.	The highlight and result of the research
Integration of renewable energy	[55]	When a large number of renewable energy sources are integrated in direct current microgrids, the microgrid faces problems, for which several approaches have been proposed, including droop control and virtual inertial control. In this study, the challenges and opportunities due to the integration of renewable energies in direct current microgrids have been investigated.
	[56]	When integrating large amounts of renewable energy sources, DC microgrids face problems due to voltage regulation, energy management, inertia control, and uncertainty management. Various approaches such as droop control, centralized control, distributed control, virtual inertia control, and uncertainty management algorithms have been proposed so far to address the above problems. The challenges and opportunities arising from the integration of renewable energy into DC microgrids are discussed in this paper. An evaluation of the advantages and disadvantages of the existing methods is provided.

and the maximum power of consumers is limited [69, 70]. Microgrids based on architecture (system topology) or distribution system into three groups: direct current microgrid [71, 72], alternating current (AC) microgrid [73, 74] and hybrid microgrid [75, 76] are divided according to Fig. 1. The choice between microgrids depends on the purpose of their application. Around the globe, many microgrids based on renewable energy have been installed and used to generate decentralized electricity in order to supply electricity to remote areas [77]. Today, DC microgrids are used for power distribution networks in automotive industries, electric vehicles, residential buildings, commercial centers, marine industries, and manufacturing industries, as well as in remote areas. A direct current microgrid is usually composed of distributed energy storage systems (ESSs) and energy resources (DERs) [78, 79]. Direct current microgrid

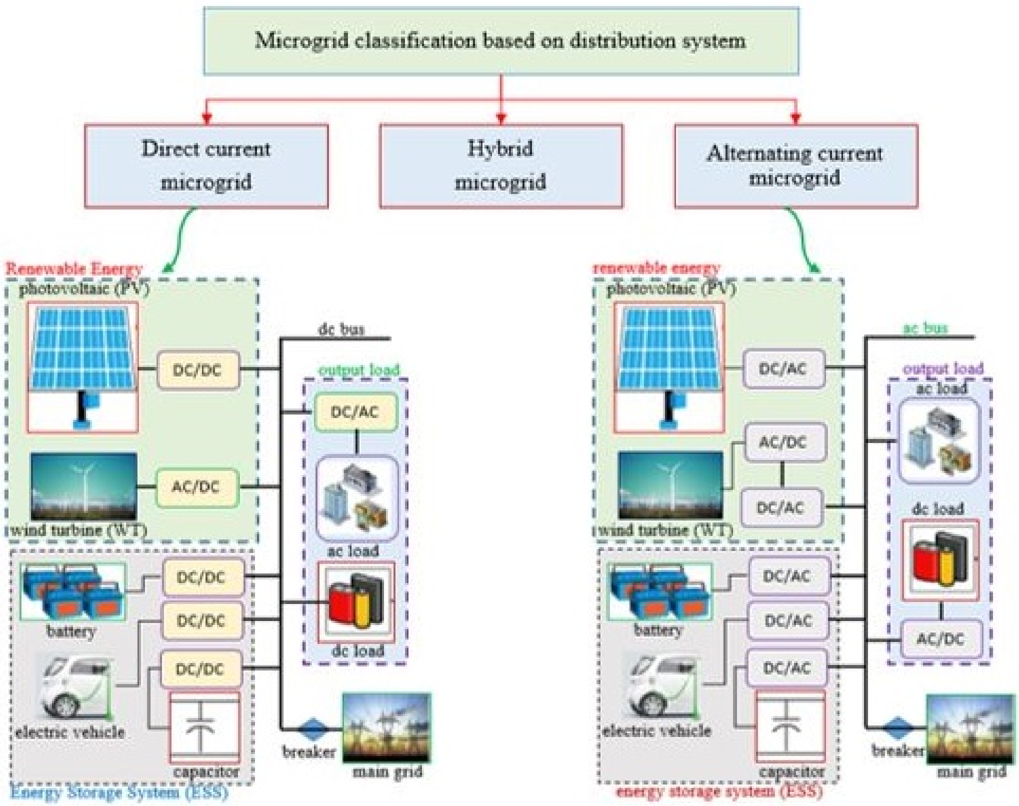

Figure 1. Classification of microgrids based on the distribution system and display of an example of direct current and alternating current microgrid system.

is a power distribution system that consists of several dc power sources, and dc loads are provided by dc/dc power converters and variable loads are supplied by dc/ac inverters [80, 81]. The dc microgrid is linked to the main network through the main dc/ac power inverter at the common connection point. Various energy sources like batteries, wind plants, solar panels, and fuel cells can exist in the dc microgrid, which work independently or in combination, and meet the power requirement of the microgrid [82, 83].
DC microgrids, like ac and hybrid microgrids, work in two main modes [84, 85]: Connected to the grid [86] and independent from the grid [87]. The island microgrid can work freely and without connection to the large-scale power grid. Ancillary services to the main power grid are provided by the microgrid in the state connected to the grid, but in the island state, maintaining the demand and generation balance is the responsibility of the microgrid [88]. Islanded microgrids increase the flexibility of the energy system [89, 90]. In DC microgrid operation in an island way, power is not transferred between the primary network and the microgrid, and the demand is balanced locally. In the grid-tied state, the dc microgrid can act as an uncontrolled load in the main grid or a controlled ac load with regulated output power. According to the intermittent character of the production of scattered resources and their unavailability, there is a need for power storage units in microgrids. High efficiency combined with simple architecture with the ability to directly integrate distributed resources has led to the application of dc microgrids in modern energy systems [91, 92]. Different kinds of distributed generation sources are used in dc microgrid [93, 94]. Photovoltaic panels [95, 96] and fuel cells [97, 98] that produce dc voltage are more suitable for use, but wind turbine generators [99, 100] that produce variable frequency, need a converter to connect to the DC bus. DC microgrids have faster transient dynamics than ac microgrids, because the rotating machines are separated from the dc grids using converters [101, 102]. In the dc microgrid, reactive power changes have no effect. And only the effect of dc voltage is considered. Also, harmonics, frequency and phase have no effect on DC microgrids [103, 104].
In short, the advantages of direct current microgrids are:

A- Less need for electronic power converter: Due to the fact that most sources of energy production work in DC mode, less number of electronic power converters are needed and the steps of power conversion are reduced, so the efficiency of the microgrid is improved [105, 106].

B- No need for synchronization: Three variables of voltage, frequency and phase are used in ac microgrid to determine the power flow, but in dc microgrid only dc bus voltage is used for energy balance in dc link. Therefore, the dc microgrid does not need frequency coordination and reactive power management. Also, the control of distributed generation sources in the microgrid is done based on DC voltage and does not need synchronization, therefore, synchronizing the available distributed generation sources is easily done [107, 108].

C- No effect of voltage reduction: Voltage reduction from the network in the case of connecting the DC microgrid to the network does not affect the internal units of the microgrid [109, 110].

D- Non-production of additional power: It does not have a standard voltage, and no additional power stage is needed to produce voltage like the ac microgrid [111].

E- Skin effect: There is no skin effect in the dc microgrid, but there is a skin effect in the ac microgrid [112, 113].

F- Integration of dc loads is done easily, but in ac microgrid, a rectifier is needed to integrate dc loads, which reduces the efficiency of the system [114].

G- Line transmission capacity: In the dc microgrid, there is no need for long transmission lines or lines with high capacity [115].

The disadvantages of direct current microgrids are:

A- Loads with high voltage: The connection of high voltage loads is accompanied by bulky and expensive converters [116, 117].

B- Initial cost: It requires initial investment, and due to having higher current levels and less time to fix the fault, there are risks of electric arc and electrocution [118].

C- Standard voltage: Due to the lack of direct connection of ac loads to the microgrid and non-standard voltage of dc loads, additional power steps are needed to adapt the dc bus level or produce ac voltage [119, 120].

D- Protection: The dc microgrid has not been developed acceptable in terms of fault resolution and lacks basic protection equipment. It has a complex protection and the protection schemes used are influenced by the time change of direct current microgrid architecture [121, 122].

E- Configuration: It is not possible to reconfigure the network [123, 124].

F- Integration with the main grid: Integrating the dc microgrid with the primary ac network is not easy and requires network reconstruction, which requires a lot of investment [125, 126].

3. Classification of microgrid control methods

Control is one of the important parts of systems and its design must be based on the system's operating conditions [127, 128]. It is difficult to control different types of distributed generation sources in the microgrid system to coordinate to create a stable voltage and frequency. The stable and economic operation of microgrids requires proper control [129, 130]. Due to the dual function of microgrids, their centralized management is not easy, so the control system in microgrid is an important research area [131, 132]. The control algorithm for the microgrid in the grid-tied operating mode is much simpler than the control algorithm for the

microgrid in the independent mode [133, 134]. Also, due to the fact that the characteristics and capacity of electricity production in distributed energy sources are different, therefore, the microgrid of the island state needs to be quickly adjusted compared to the microgrid of the state connected to the grid [135, 136].
A group of microgrid resources such as generators, batteries and controllable combined heat and power production and another group such as solar cells, water turbines and wind turbines are possible (uncontrollable) distributed generation, which are used to generate power [137, 138]. An important issue in microgrid control is related to controllable resources. Therefore, in order to control the microgrid, the presence of at least one of the controllable resources in the microgrid is necessary for the stability of the microgrid [139, 140]. With the development of dc microgrids, their control strategies have attracted more attention [141, 142]. Control methods have an important effect on the transient behavior of dc microgrids, so they will have a significant effect on their protection aspects [143, 144].
Different microgrid control methods are shown in Fig. 2. Control strategies play a key role in improving the implementation and efficiency of DC microgrids.

3.1 Regulatory control system (hierarchical control)

Due to the application of direct current microgrid, a reliable and efficient control scheme such as hierarchical control is required to control dc microgrids, and for this reason, this method has been widely proposed in studies by researchers [145, 146]. In a microgrid, to further enhance stability, different control levels are used sequentially, each of which has a duty in relation to stability. In the regulatory control system method (hierarchical control) or in other words multi-level control, microgrids work using several control loops [147, 148]. In general, hierarchical control is used to standardize the performance and capabilities of microgrids [149, 150]. The hierarchical control structure includes local, first-level, second-level, and third-level controllers, ranging from milliseconds to hours or days [151, 152]. Each stage is responsible for microgrid regulation at various levels, whose basic tasks are organized in Fig. 3 [153, 154].
Management of the appropriate power sharing rate between distributed energy sources is performed at the primary level control, which is typically distributed without communication connections. In order to decrease voltage fluctuations and enhance energy quality, secondary level control is employed [155]. Tertiary level control is used for long-term electricity market information planning [156, 157]. Table 2 depicts the comparison of control levels in the microgrid in terms of the task and purpose of the control level. The hierarchical structure of direct current microgrid is divided into two groups of two-stage regulation architecture and three-level control architecture. For the dc microgrid, there are three levels of control from the bottom up, including the converter control level (control of various topologies of the converter), the voltage coordination level (coordinating the power flow in the power network), and the level of energy management (optimizing functions in a wider range using the information network) is defined. Therefore, the reliance on communication decreases and the strength of the control system increases [158, 159]. Fig. 4 shows the hierarchical control structure in a direct current microgrid [160, 161].

3.2 Supervisory controller (based on communication method)

Communication is one of the main elements of the control system. Microgrid controllers are divided into three fundamental control sections, including centralized regulation, semi-centralized regulation, and distributed regulation based on the communication link and control architecture of power systems [162, 163]. Each of these three control methods has specific characteristics, but having better performance and stability for micrograds is their common goal [164, 165]. Fig. 5 shows a sample of the above designs.
Proper management of continuous energy between production units and consumption loads is possible through a centralized control system with communication between different units. Direct current microgrids allow for centralized control through the use of a central controller and a digital communication network that links sources and loads. Hierarchical control is more reliable than centralized control. One of the weaknesses of this method is being affected by the communication line. Decentralized coordination is one of the control strategies of DC microgrids. Digital communication between different system units is not required in decentralized control, and therefore decentralized control

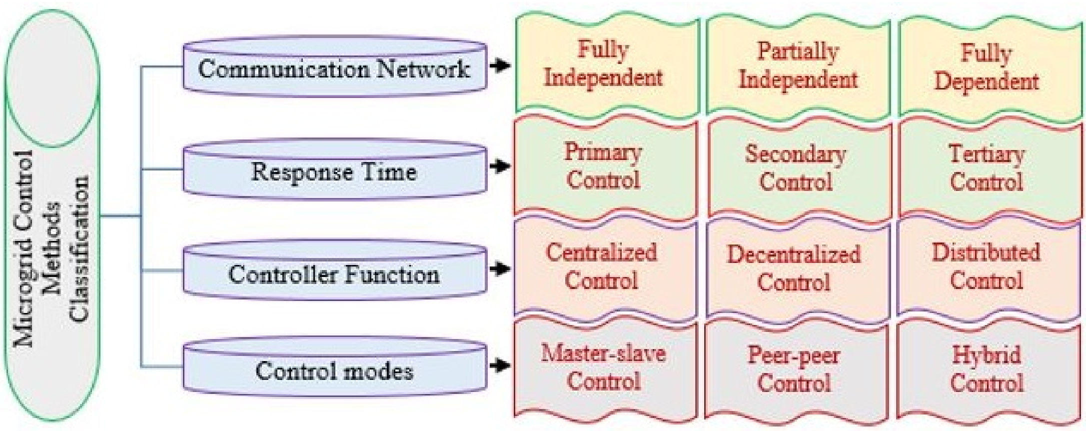

Figure 2. Division of control methods in microgrids.

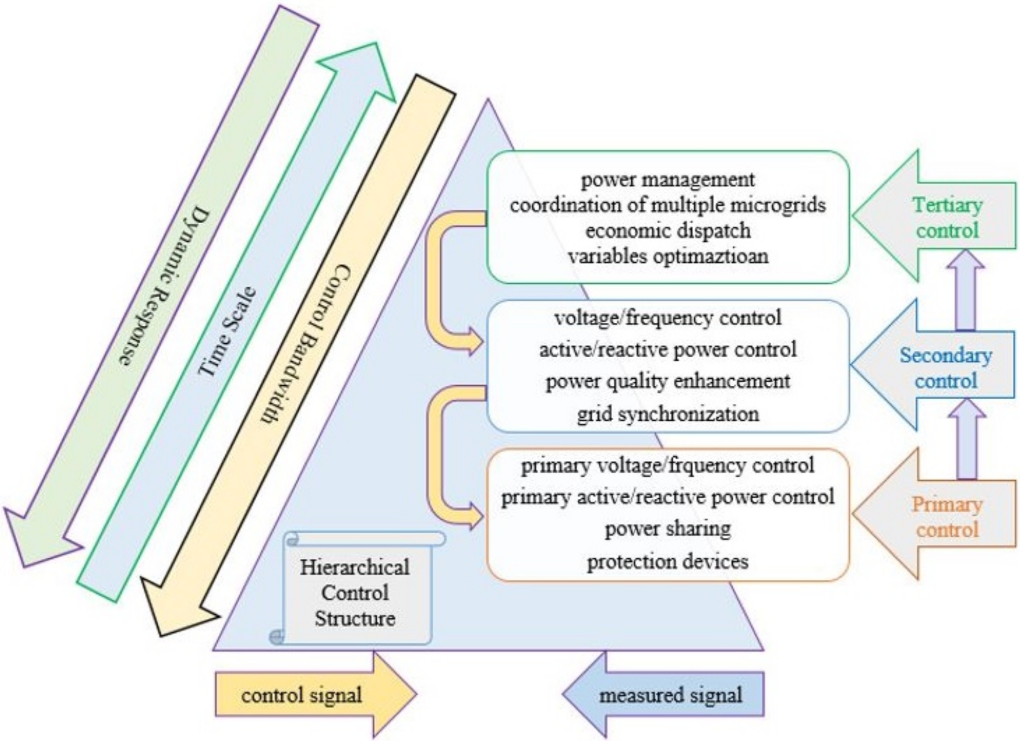

Figure 3. The role of hierarchical control levels in microgrids.

is a reliable and simple control scheme [166, 167]. This method is inherently functionally limited because the information of other units is not exchanged, and the effectiveness and reliability of the method is also affected by the accuracy of the sensors. The decentralized control approach is usually funded on the droop regulation method [168, 169]. In the distributed method, every local regulator communicates with its neighboring controllers to achieve some of the advantages of the centralized method for the microgrid [170]. Distributed control is different from central control, in other words, there is no central unit and the digital communication line is the interface between local controllers. One of the main advantages of this method is the complete preservation of performance when some communication links fail [171]. By comparing the characteristics of the architectural arrangements of the control systems, it is clear that the majority of the computational burden and computational cost for the central controller of the microgrid is imposed in the centralized control, while the least amount will be imposed in the local controllers. Both centralized and decentralized control are also more difficult to implement than the more complex distributed control [172].

The advantages and disadvantages of the three supervisory control methods for comparing their performance are summarized in Table 3 [173].

3.3 Classification based on control methods

Control strategies in microgrids are divided into three groups, master-slave, peer-to-peer, and hybrid based on control modes [174, 175]. A master-slave regulation approach is simple and easy. A master-slave control strategy is a common example of a centralized regulation method. The master-slave approach is a model of communication or asymmetric control in which a distributed source as the master unit controls one or more distributed sources as a slave unit [176, 177]. In the master-slave control structure to sustain the microgrid in island operating condition, the voltage and frequency of one of the distributed generation

Table 2. Comparison of performance levels in hierarchical control for a microgrid.

Level number	Controller aim	Controller implementation
Primary	* Primary stability of frequency or angular velocity	* Prevent voltage or frequency collapse Basic control working in a few seconds
Secondary	* Frequency or voltage droop control	* Creation of steady state error in basic variables due to events such as fragmentation, load change and error occurrence
Tertiary	* Controlling extensive microgrids with multiple controllable voltage sources	* Creating coordination by the main control in the micro-grid Power management control in the microgrid

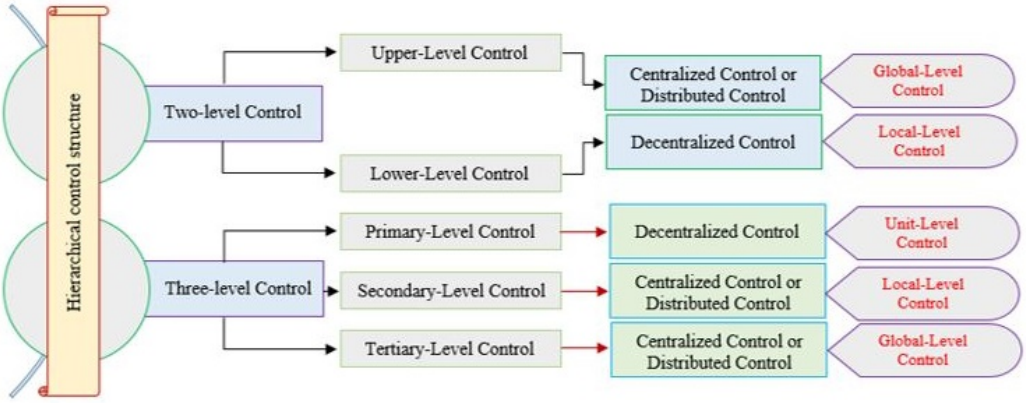

Figure 4. Hierarchical control structure in direct current microgrids.

sources or power storage (master controller), for other distributed generation sources and loads (slave controller), as the base value is considered. Each slave controller makes a decision based on the main controller for its operation mode. One of the disadvantages of this method is the excessive dependence on the main unit [178, 179]. At the moment when there is no reactive or active power in the network, it depends only on the main unit to adjust the system. The control strategy of the main unit during network failure has an important effect on the microgrid stability [180, 181]. Fig. 6 shows a display of master-slave control that the system has one master unit and two slave units.
In peer-to-peer regulation, all distributed generation resources in the microgrid control system have the same status. In this method, the controllers use the measurement signal (voltage and frequency) at the connection point to control each part of the microgrid under the same conditions. In other words, control does not depend on communication and there is no hierarchy among controllers. By connecting or disconnecting any generator, the microgrid can continue to work and energy needs can still be met. The peer-to-peer control architecture can take advantage of the flexibility and resilience of microgrids [182, 183].

4. Droop control

The microgrid may have multipurpose power electronic converters that connect sources, loads, and storage systems to the bus [184, 185]. Coordination of the performance of supervisory control systems, energy management and protection in microgrids is done using advanced power electronic converters [186, 187]. Parallel use of electronic power converters to achieve power sharing is one of the

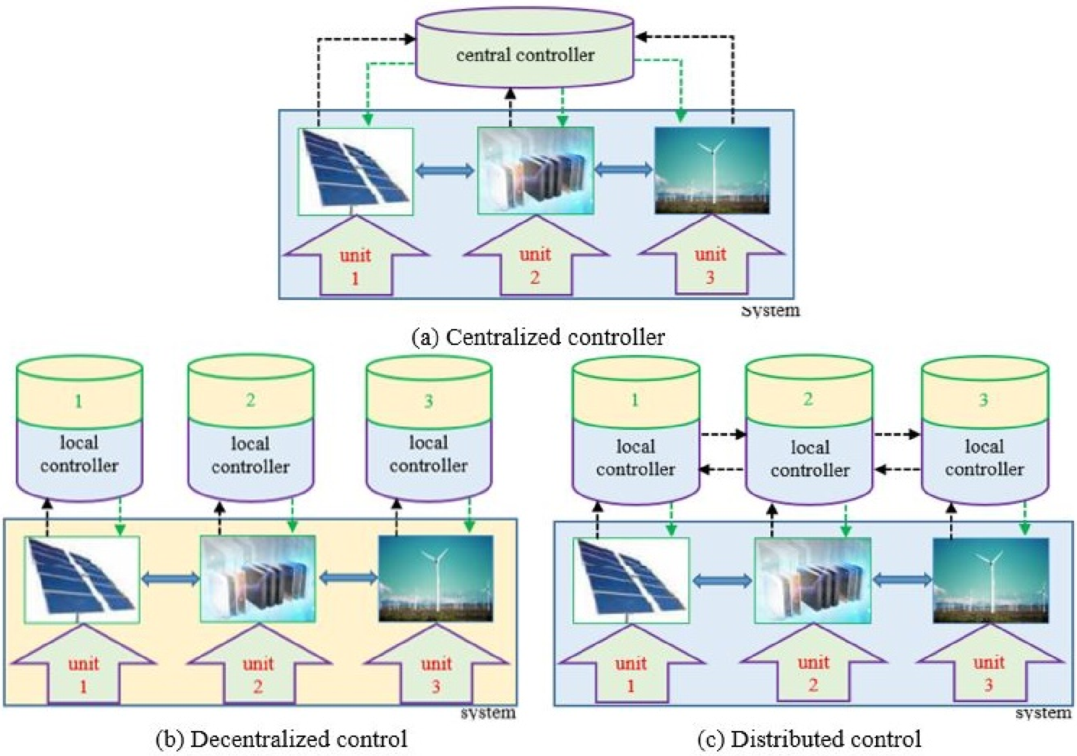

Figure 5. Division based on control system architecture.

Table 3. Advantages and disadvantages between three methods in microgrid supervisory controller for comparison.

Method / Quantity	Centralized	Decentralized	Distributed
Control accuracy	High	Low	Medium-High
Scalability	Medium	High	Medium
Computational and communication burden	High	Low	Medium-High
Response speed	Low	High	Medium
Economic performance	Medium	Low	Medium-High
Computational complexity	High	Low	Low
Two-way communication infrastructure	Medium	Low	High
Implementation difficulty	Low	Medium	High
Network management complexity	Medium	High	Low

important aspects in a dc microgrid. In case of coordination between electronic power converters, it is possible to direct the energy flow in the microgrid system [188, 189]. Various methods have been presented for the parallel operation of microgrids, which are divided into two groups of load sharing and droop controller based on the connected communication network [190, 191]. Droop regulation is a widely used approach in dc microgrid to equalize current distribution between converters like reactive power distribution in ac microgrid. Conventional droop control works by adding virtual resistance in the line to equalize the current distribution. Droop regulation is a typical example of decentralized regulation methods that are widely utilized in dc microgrids [192, 193]. Decentralized load distribution approaches are usually implemented at the first level to achieve proper resource and load management. Droop control is used to achieve the goal of plug-and-play operation in microgrids [194, 195].
Droop control is more reliable than other types of control strategies for DC systems because there is no breakdown point and only bus voltage details are required [196, 197]. Droop control methods are classified into two groups based on the variable selected for feedback in the voltage source converter according to Fig. 7 [198, 199]. Fig. 8 shows the active current-power droop strategy for two cases where the dc voltage is calculated, and the injected power or current is managed based on the droop curve. Fig. 9 shows the current-voltage droop strategy for two cases where the power or current is calculated, and the dc voltage is adjusted based on the droop curve.
Droop control methods are classified into conventional droop control and advanced droop control [200, 201].

4.1 Common droop control

To equalize load sharing between distributed generation units in dc microgrids, automatically like sharing reactive power in ac microgrids, the droop method can be used [202, 203]. Droop regulation is a scheme to share current among power converters in DC microgrid [204, 205]. When using conventional droop regulation, there is a trade-off among dc bus voltage stability and power sharing between distributed generation sources [206]. The equal current in the normal droop control causes a decrease in the DC bus reference voltage and the non-uniformity of the voltage regulation in each node, so that as the current share approaches the regulation point, the bus voltage deviation increases. Im-

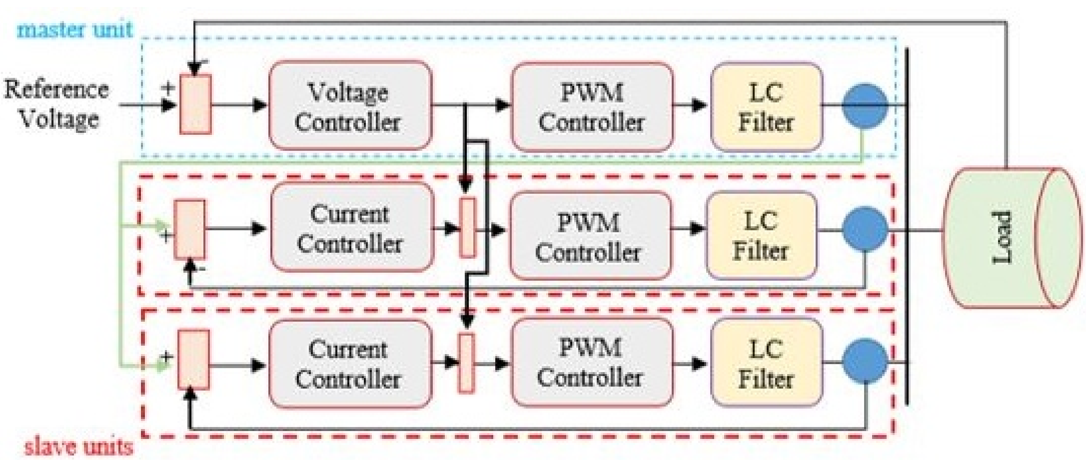

Figure 6. Schematic representation of master-slave control.

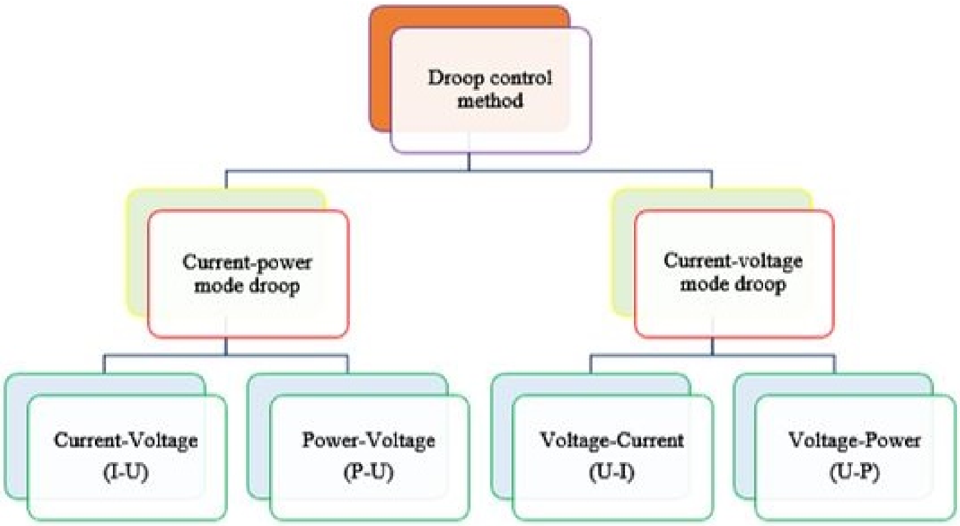

Figure 7. Classification of droop control methods in direct current microgrid voltage converter based on feedback variable.

provement of voltage deviation causes imbalance of current sharing [207]. The traditional droop control approach utilizes constant droop resistance, likely with the control goals of precise current sharing and voltage management. The voltage variation is increased by an uneven line resistance because the current sharing error is decreased [208, 209]. A dc micro grid's stability (limited droop gain) and load distribution accuracy (high droop gain) are two competing goals when implementing droop management [210].
The control scheme based on virtual basis is a suitable method in converters to modify their dynamic profiles [211, 212]. Virtual impedance is a lossless circuit-based control concept. In the dc-based energy system, the constant load creates an incremental negative resistance that may worsen the stability of the entire system [213, 214].
The droop control method in dc microgrid, like ac microgrid, is not based on production power, and for its implementation, feedback is taken from the output current using a virtual resistor. Concepts of virtual impedance in dc microgrid are different from ac microgrid. In ac microgrid, virtual impedance is used to change the output impedance of the power converter, so that the effect of reactive and active energy coupling can be neutralized, but in dc microgrid, virtual impedance is used streamlet for power distribution. Conventional droop control is used to share equal current between converters by adding virtual resistance in different lines. Droop control prevents circulating currents between converters. Figs. 10 and 11 show how to implement droop control in dc and ac microgrids, respectively [215, 216]. Droop control is similar to primary frequency regulation in a traditional electric power system. One of the advantages of the Droop strategy is that there is no need for communication signals between parallel units. However, implementing droop control without dropout communication has poor performance, and may even cause voltage instability [217]. Poor transient performance, ignoring load dynamics, inadequate distribution network performance, failure to offer precise distribution of power with output are common disadvantages of droop control method, which limits its application in a modern power system [218].
In islanded dc microgrids, the inertia is very low and the dc bus voltage will be very sensitive to disturbances. In the case of microgrid operation as an island, the distributed generation source that uses the droop control strategy is effective in managing the frequency and voltage in the microgrid. In the parallel dc regulation framework, the droop regulation approach is widely used, in which the power distribution rate is defined by increasing the loss. When the droop gains are set at a fixed value, the output current of each distributed energy source has a fixed slope. It is obvious that the droop control with constant droop coefficient cannot deal with the situation where the impedance of the line is unbalanced, because the difference of the impedance of the transmission line will cause the deviation of the terminal voltage and the

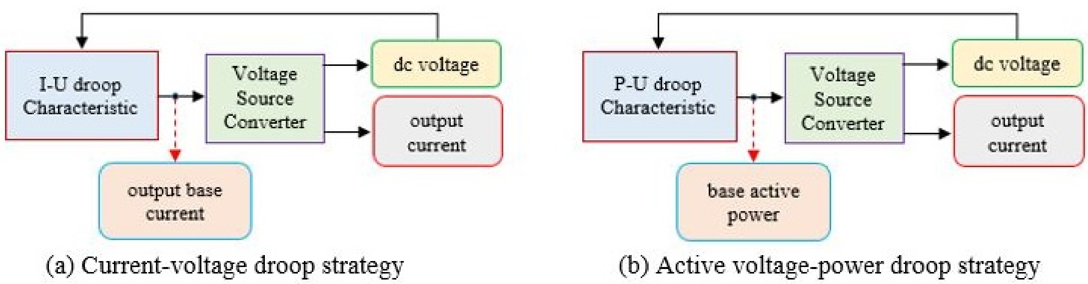

Figure 8. Active current-power mode droop regulation.

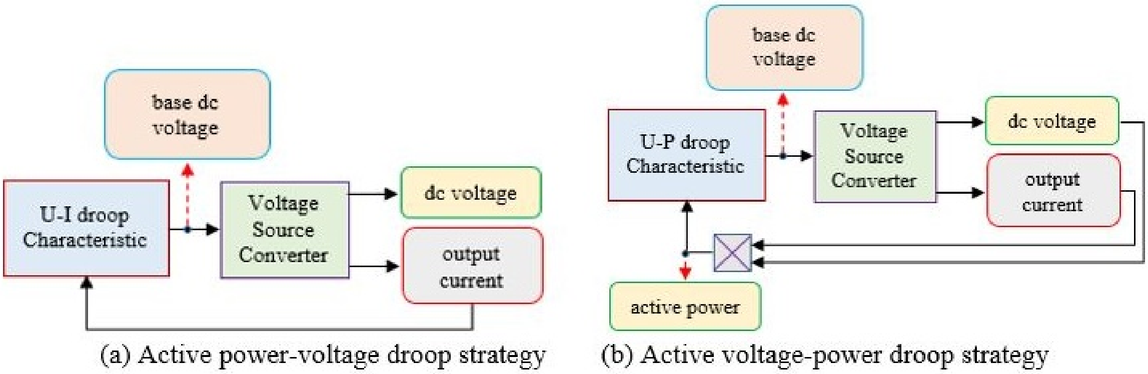

Figure 9. Current-voltage droop control.

phase of the parallel inverter. Conventional droop controller techniques are not easily able to provide satisfactory performance, because the selection of high droop controller gain for fast power sharing reduces the system stability [219].

4.2 Advanced droop control

Common methods of voltage and current droop due to load increase cannot correct the transient system response without losing the accuracy of power sharing. Also, the addition of distributed energy sources, due to having different characteristics and capacities, makes the system need to be adjusted quickly. Advanced droop regulation includes inverse droop regulation [220], nonlinear droop regulation [221, 222] and adaptive droop regulation [223, 224] is divided [225].

A. Reverse droop regulation

Inverse droop regulation is an alternative approach employed for low voltage microgrids. The inverse droop regulation scheme is similar to the common droop control and its implementation is simple [226]. In reverse droop control, active power is controlled by a voltage droop and reactive energy is managed by a frequency droop. Among the disadvantages of reverse droop regulation, it can be pointed out that it is not compatible with high pressure lines, which are mainly inductive, and the failure to implement active power dispatch performed by transmission system operators at very high levels of the network [227, 228].

B. Adaptive droop control

Adjusting the controller parameters in an adaptive control system is done automatically to compensate for the changing conditions of the process [229]. In this scenario, the closed-loop framework will be periodically tested and the test characteristics of the new controller settings will be determined automatically [230, 231].

Choosing a high droop gain weakens the voltage regulation, and choosing a low droop gain weakens the load sharing, so in adaptive droop control, the droop gains changes during the operation according to the circuit data to determine the purpose; for power sharing [232, 233]. In the adaptive droop control, more parameters need to be defined than the normal PI controller.

To address nonlinearity in the system, dc microgrids can use an adaptive droop technique, as illustrated in Fig. 12 [234]. Two regulation loops, one with proportional-integral feedback and the other with droop, make up this circuit. The PI controller is used to set the droop resistance, which eliminates the error of sharing the micro grid's current. In addition, the secondary loop makes use of an adaptive PI controller to change the dc bus voltage via adjusting the droop lines. This approach solely requires the transmission of DC bus current and voltage to individual units via low-bandwidth communication channels in the microgrid.

C. Non-linear droop control

In conventional droop configuration, a constant droop resistor is used to make a trade-off among the voltage regulation and power distribution accuracy. To improve the performance of both areas in traditional droop regulation, the use of nonlinear droop regulation for multiple parallel dis-

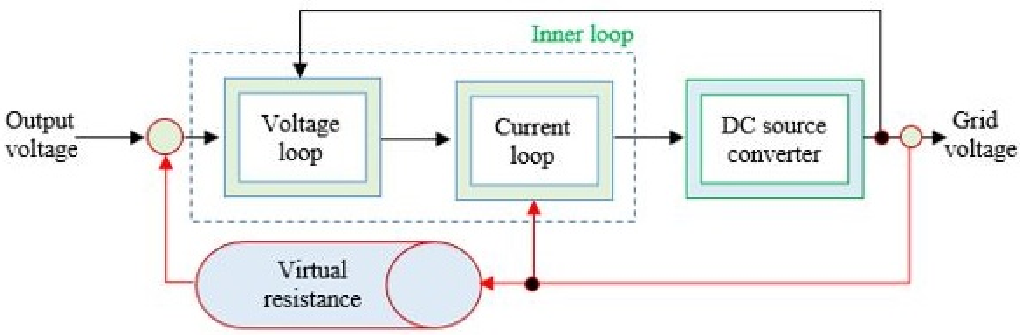

Figure 10. Implementation of droop control in direct current microgrid (initial level control).

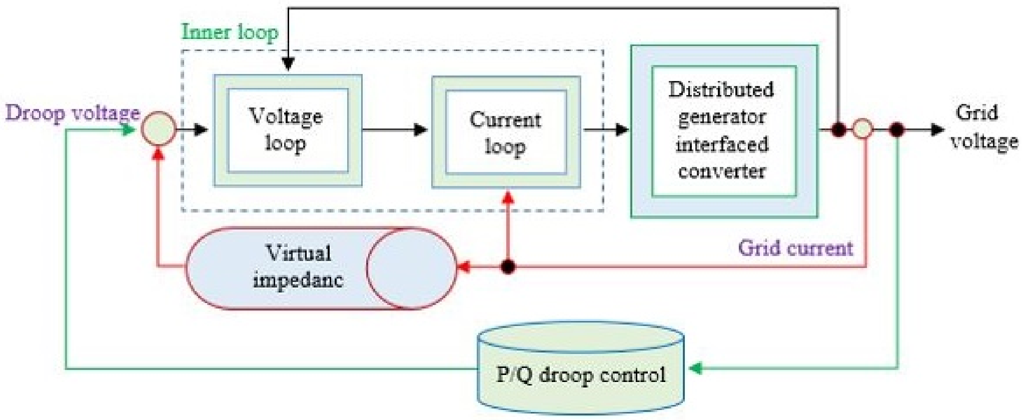

Figure 11. Implementation of droop control in alternating current microgrid (initial level control).

tributed sources in a DC microgrid is presented [235, 236]. In the non-linear droop control, instead of the linear droop relationship, the non-linear droop with the slope of the droop curve can be used to adjust the increase in current distribution. In nonlinear droop control, the droop resistance changes as a function of the power converter output current, and increasing the output current of the converter increases the value of the droop resistance. Fig. 13 illustrates the comparison of the droop regulation design curve in two modes conventional droop design and nonlinear droop design [237]. The nonlinearity in the droop feature indicates that the droop coefficient is high and low at maximum load and light load, respectively, so it improves the general operating implementation of the droop regulation.

5. Literature review

Load sharing and optimal voltage regulation are affected by various factors such as sensor calibration errors and cable resistance. Three high droop coefficient approaches, polynomial droop curve approach and polynomial droop curve approach with voltage compensation, all three methods are completely decentralized are presented in [238]. These approaches reduce the effect of cable resistance and sensor calibration errors, and only require local information.

Decentralized reverse droop control for the configuration of dc-dc converters with parallel connection at the output and series connection at the input for high input voltage and low output voltage applications is presented in [239].

This approach does not need a central regulator, and the modules are independent, and the voltage reference increases as the load rises. The characteristic of adjusting the output voltage is unaffected by the input voltage.

Fault detection and fault current control in photovoltaic-based dc microgrids have been investigated in [2021-202] [240], where an adaptive droop scheme is proposed for fault current control, using virtual resistance droop and converter output reference voltage control. The droop method is used to control power sharing among converters with reference control.

Voltage regulation and load sharing among multiple distributed generators are the objectives of the control system, and distributed control techniques have been widely adopted

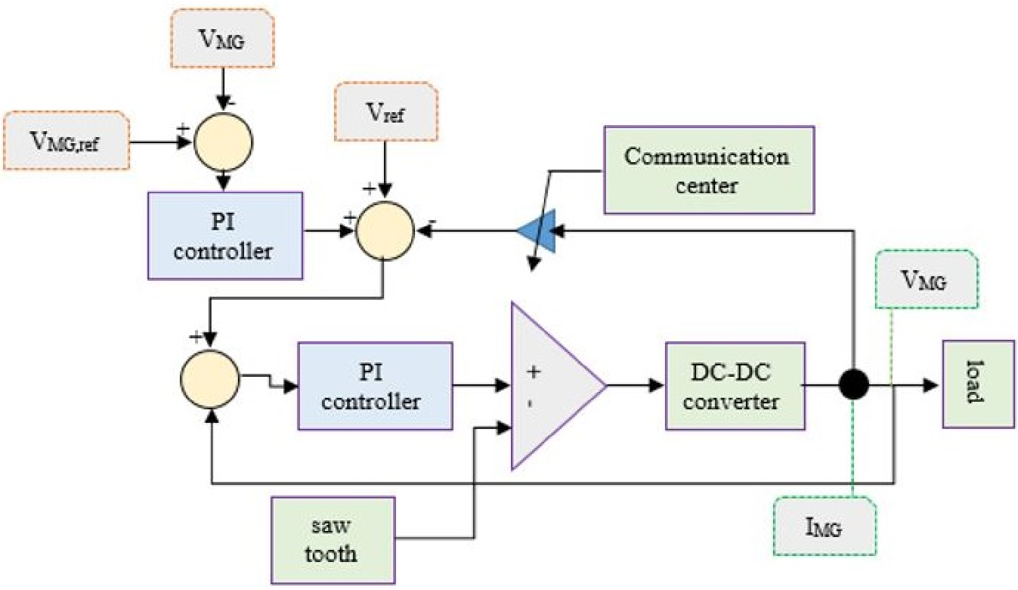

Figure 12. An example of adaptive droop control including two loops.

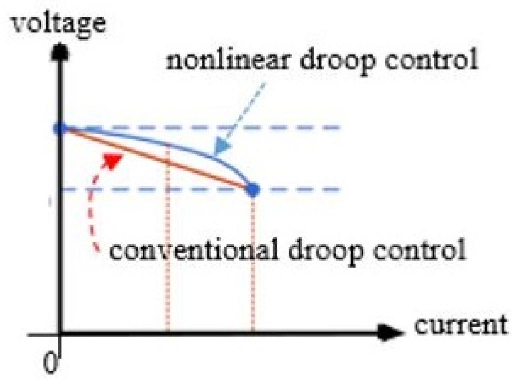

Figure 13. Comparison of the design curve of droop control in two conventional and non-linear modes.

to achieve these two objectives. Most distributed methods use two additional regulatory terms to adjust the deviation caused by conventional droop control. A cooperative distributed controller for droop control of distributed generators is presented in [2025-49] [241], which determines the average voltage regulation and proportional current sharing based on an integrated approach. Therefore, it does not require further correction conditions and has a simple control structure. The stability of the control system is analyzed using a small signal model and the effectiveness of the proposed method is demonstrated.

In order to ensure that the converters in a dc microgrid are sharing current fairly and that voltage recovery is functioning properly, the authors of [242] suggest a distributed secondary control approach. Droop gain and line resistance are used to define a quantity referred to as "virtual voltage droop" in the suggested method. One more thing: The feedback signal doesn't need any dc bus voltage. Considering that there is no requirement for loads, the control method can be used for resistive loads and constant power loads. The secondary control signal for resistance loads and constant power is shown in Fig. 14 and 15.

A hybrid master-slave control strategy for operating multiple distributed production units in a microgrid is proposed in [243]. The simulation results of master-follower hybrid control strategy for multiple distributed production units in a microgrid are shown in Fig. 16, 17 and 18. As can be seen, the duration of the simulation is 4 seconds. The common load of 4 kW and 4 kW is initially supplied by three distributed generation sources, and the DG follows the traditional PQ control. At the moment of 0.5 seconds, the shared load suddenly increases to 6 kW and 5 kW. At the moment of 1 second, the load changes again to 8 kW and 6 kW. At the 1.5 second moment, the DG adopts improved droop control. At the moment of 1/2 second, common load of 2 kW and 1 kW is entered. At the instant of 3 seconds, DG3 is switched off, and the other two sources supply the common load. When the traditional PQ control is adopted, the system frequency and voltage droop is high, and its energy quality is poor. However, DG slave can participate in system load power regulation at the same time and reduce voltage and frequency droop.

A coordinated adaptive droop control method to optimize

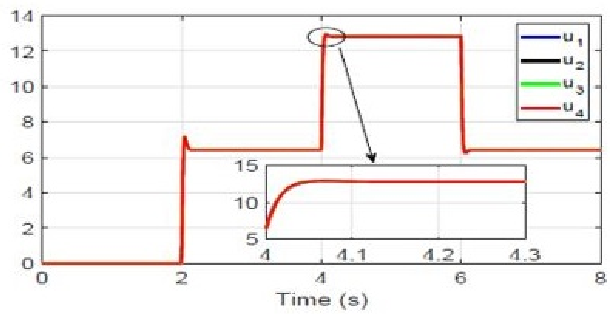

Figure 14. Control signal for resistive loads.

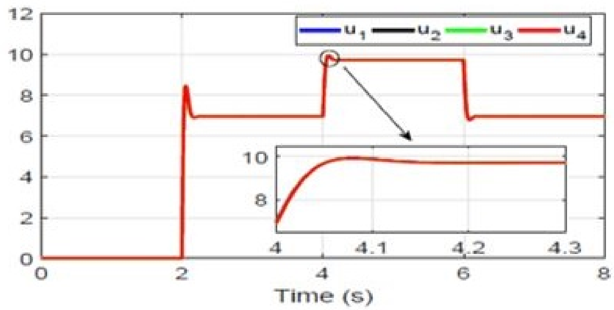

Figure 15. Control signal for constant power loads.

power distribution in a dc microgrid is presented in [244], in which to solve the problem of economic distribution of the microgrid using a hierarchical controller, an optimal solution of an economic regulator based on consensus is suggested. In this method, the droop regulation reference is determined through the economic regulator, and by maintaining the balance of the power system, the convergence of the output energy to the reference is guaranteed. The numerical outcomes indicate that the use of this regulation scheme has reduced the cost of the infrastructure along with increasing the reliability and increasing the convergence speed of the algorithm.

A large difference in the line resistance reduces the accuracy of current sharing of the system, which can be used to increase the loss factor to enhance the accuracy of current distribution, but it involves a droop in bus voltage. To

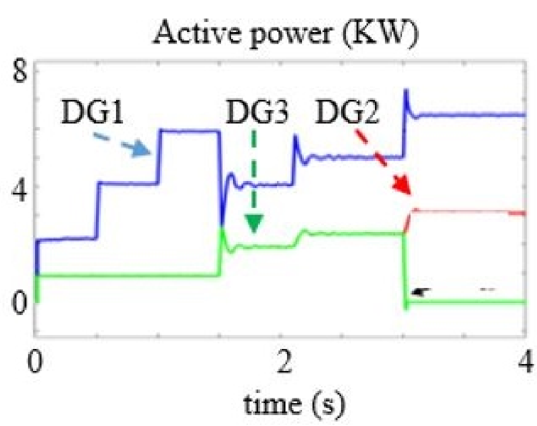

Figure 16. Active output power of distributed generation sources.

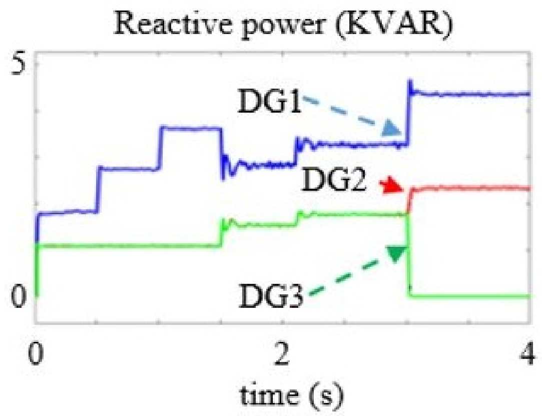

Figure 17. Output reactive power of distributed generation sources.

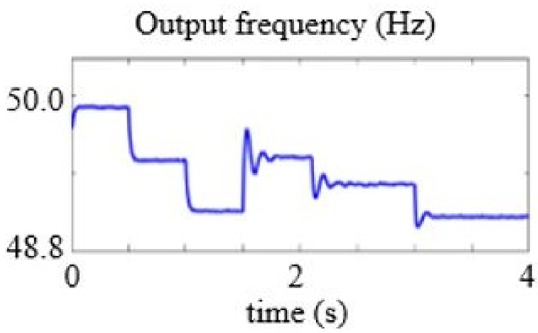

Figure 18. System output frequency.

solve the problems between load current distribution and voltage regulation in conventional droop regulation, a hierarchical regulation algorithm based on droop regulation improvement with a fuzzy logic controller to improve the droop curve is presented in [245]. The fuzzy logic controller changes the resistance droop. The droop factor regulator and the current regulator both compensate for the slope of the droop curve and the voltage regulator compensates for the longitudinal gap of the droop curve.
A regulation method for power fluctuation damping in a multi-source dc microgrid is presented in [246]. The hybrid power conversion system controller for power management consists of a multi-loop voltage regulator and a virtual impedance single-loop regulator. A dynamic droop coefficient is used in power sharing control to neutralize low frequency oscillations.
The virtual impedance adjustment method based on successive approximation to accurately compensate for the mismatch between line impedances is presented in [247]. The adaptive virtual impedance adjustment funded on the error between the real output reactive energy and its reference is combined with the Q-V droop control, and then in each cycle, the virtual impedance adjustment reactive power reference is adjusted with the last estimate of the Q-V droop control.
Virtual negative resistance counteracts the line resistance against the isolation power. Conventional droop control is impractical for low-voltage microgrids, especially when the line impedance among distributed production parts is resistive to match the reactive and active power of distributed production. An improved droop control based on virtual power source and composite virtual impedance, composed of a negative resistance and a negative inductance, is proposed for low voltage microgrid in [248].
The imbalance of stored energy causes challenges in microgrid control due to the addition of distributed energy storage units. A decentralized strategy based on fuzzy logic is presented in [249] to balance the stored energy with distributed battery power storage systems in a dc microgrid, where the virtual resistances of droop regulators are modified according to the state of charge of each power storage unit, they become also, the virtual resistance is set to reduce the voltage deviation in the common dc bus, and the units are controlled using local variables only.
To solve the problems of the limitations of the traditional droop regulation scheme, in [250] an improved droop regulation scheme funded on low-bandwidth communication is presented to recover the dc bus voltage and increase the accuracy of current distribution, which is an approximate configuration. It is shown in Fig. 19, where u represents the dc voltage and I represents the dc current. As can be seen, low-bandwidth communication has been used to transmit the output voltage and current of the converters. Also, to achieve proportional load current distribution, the traditional droop regulation approach has been used. By choosing the load resistance of 200 ohms, the simulation results of voltage recovery and current distribution accuracy are shown in Figs. 20 and 21. As can be seen, the dc voltage of the two converters has been recovered after applying the proposed control method, and the accuracy of current sharing has also increased.
An improved droop control strategy for dc microgrids is presented in [251] in order to create appropriate load flow and power sharing in parallel distributed energy sources. The simulation results show the application of the droop strategy in different rated powers and impedance of the connection cable.
In heavy load conditions, with the increase in the output current of scattered units, the need for accurate sharing of the load current increases. An adaptive control method for dc microgrid applications is presented in [252], considering both current sharing parameters and acceptable voltage regulation based on load conditions. In this method, by increasing the load level and accurate sharing of the cur-

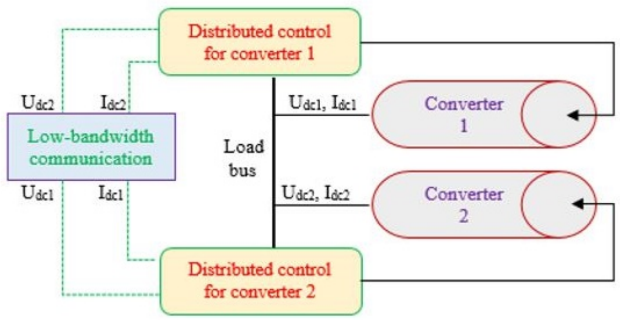

Figure 19. Approximate configuration of control system based on broadband communication.

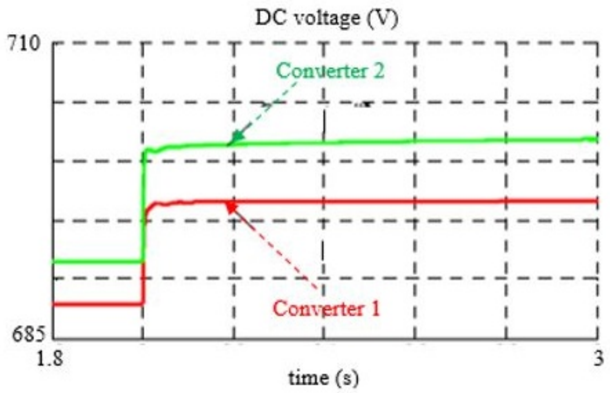

Figure 20. Voltage recovery after applying the control method.

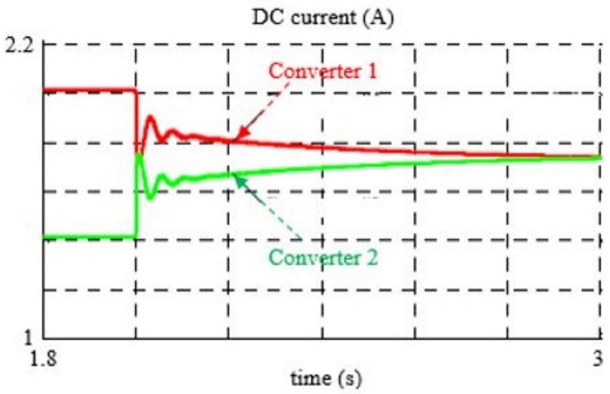

Figure 21. Flow sharing accuracy after applying the control method.

rent, the benefits of the equivalent droop increase. The performance and stability have been evaluated in a linear model and the laboratory results together with the simulation results in the time domain evaluate the correctness of the method.
In dc microgrid, a distributed local control scheme with base droop control is presented in [253], where microgrid stability with two sources for proper load sharing and voltage improvement capability considering line resistance has been checked. In this method, the centralized controller is used in order to zero the electric current of the connecting line for constant conditions in each area. The performance of the control scheme is shown with the simulation results compared to the normal droop control and hierarchical secondary control.

6. Conclusion

In this study, the application of droop control in direct current microgrids was investigated. The classification of microgrids was explained based on the type of control and distribution system. Two control objectives of accurate load power sharing and bus voltage regulation are important and vital to ensure power quality and reliable operation of dc microgrids. DC bus voltage adjustment is done by adopting an external secondary control loop, but the lack of proper power/load current sharing between the converters due to the incorrect matching of the feeder resistors should be considered. Due to the existence of different distances and the complexity of microgrids, the impedance of the lines between the feeders of scattered productions and loads is different. Droop control is a programming method for the output impedance in the microgrid without the need for a communication line, in which the output voltage decreases linearly with the output current or power. Droop control method is a popular and well-known technique for sharing load power, which is widely used in DC microgrids. In this control strategy, the reference voltage of each source is determined based on the nominal output voltage, output current and loss factor, where the power sharing rate is determined by increasing the loss. The common method of droop control is achieved by linearly decreasing the dc output voltage with an increase in the output current, which has two limitations: a- reducing the accuracy of sharing the output current due to the inaccuracy of the output voltage of each converter and b- increasing the deviation of the dc bus voltage due to the droop action, which are solved by using current sharing loops and secondary control loop, respectively.

Ethics

The authors declare that the present research work has fulfilled all relevant ethical guidelines required by COPE.

Authors contributions
Authors have contributed equally in preparing and writing the manuscript.

Availability of data and materials
Data underlying the results presented in this paper are available from the corresponding author upon reasonable request.

Conflict of interests
The authors declare no conflict of interest.

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