

¹Shilpa K. Patel²Rajnikant H. Bhesdadiya³Hitesh M. Karkar⁴Shilpa L. Kaila

Various Load Sharing Strategies Used in DC Microgrids



Abstract: - This paper provides a review of various load sharing strategies used in DC microgrids. DC microgrids usually utilize parallel connections of DC-DC converters to improve system reliability and flexibility. However, when connecting multiple converters in parallel in a microgrid, the resistance of the cables becomes a critical factor. Unequal load distribution and inadequate voltage control result from cable resistance, leading to the generation of circulating current. The equal load sharing can be achieved by active load sharing and passive load sharing methods. These two broad categories encompass a wide range of control schemes. This paper provides a comprehensive analysis of active and passive load sharing strategies, highlighting their advantages and disadvantages. Very few researchers have explored the influence of cable resistance on load sharing and voltage regulation. Also, the effect of circulating current on the converter is a relatively unknown factor that must be identified and reduced to the greatest extent possible. This paper is a valuable resource for future researchers who are interested in studying load sharing and related control techniques

Keywords: Parallel Converters, Circulating Current, Voltage Regulation, Active Load Sharing, Passive Load Sharing.

I. INTRODUCTION

Nowadays, renewable energy offers clean and low-cost Energy derived from sustainable sources such as solar radiation, wind, geothermal heat, and biomass. The microgrid concept is introduced to use such renewable resources to generate electricity [1]. The distributed generation (DG) units, also known as small generators, can function independently in isolated regions, such as rural areas, or be connected to utility grids [2]. The employment of renewable energy sources in the microgrid serves as an essential component for the development of future energy networks, offering sustainable and resilient solutions to meet long-term energy requirements [3].

The microgrids are classified as alternating current (AC), direct current (DC), and hybrid microgrids. The microgrids operating and supplying AC power into the integrated utility system are termed an AC microgrids. Integration of AC microgrids is easy with the existing power grids without the requirement of any specific control approach [4]. However, AC microgrids encounter various challenges. For instance, the distributed generators must be synchronized and there are issues related to the flow of reactive power, harmonic currents, and energy imbalances in three-phase systems [5]. The AC microgrid faces a significant disadvantage in synchronizing with the main grid, as it requires to match frequency, phase angle, and voltage magnitude with the main grid [6]. Therefore, the power quality standards for an AC microgrid are stringent. Also, AC grid-connected rectifiers have significant losses due to device conduction losses [2]. Hybrid microgrids are composed of both AC microgrids and DC microgrids. Hybrid microgrids address issues associated with both AC and DC microgrids. Nevertheless, setup, supervision, and control of hybrid microgrids are complicated and expensive [7].

Hence, the concept of a DC microgrid emerged because the majority of Distributed Energy Resources produce DC power and there is an increasing utilization of contemporary DC loads. The rapid development of renewable energy sources and DC microgrids offers many applications, including commercial and residential buildings, zero-net-energy buildings, renewable parks, industrial applications, data centers, telecommunications, electric vehicles and charging stations, ship networks, railways, etc. [8],[9]. Figure 1 illustrates the common structure of a DC microgrid [10]. The DC microgrid offers numerous advantages compared to the AC microgrid [11],[12]. Most

¹ * Research Scholar, Gujarat Technological University, Ahmedabad, Gujarat, India

² Assistant Professor, Department of Electrical Engineering, L. E. College, Morbi, Gujarat, India

^{3,4} Assistant Professor, Department of Electrical Engineering, G. E. C., Rajkot, Gujarat, India

renewable energy sources generate DC power that can be connected to the DC grid without a rectifier. DC microgrids have no reactive power control or frequency regulation, no grid synchronization issues, no inrush current due to transformer absence, low converter conversion losses, and no skin effect. Thus, Future DC microgrids can improve grid efficiency, reliability, and cost optimization.

However, certain challenges need to be addressed in DC microgrids. These include effective interconnection schemes between DGs and the DC grid, ensuring proper voltage regulation, achieving equal load sharing, circulating current, implementing maximum power point tracking, protection issues, and grounding issues [13]. In a DC microgrid, the renewable energy sources can be connected separately. Usually, the interfacing converters are connected in parallel [14]. In the parallel configuration of converters, equal load sharing among the converters and voltage regulation has been a key issue.

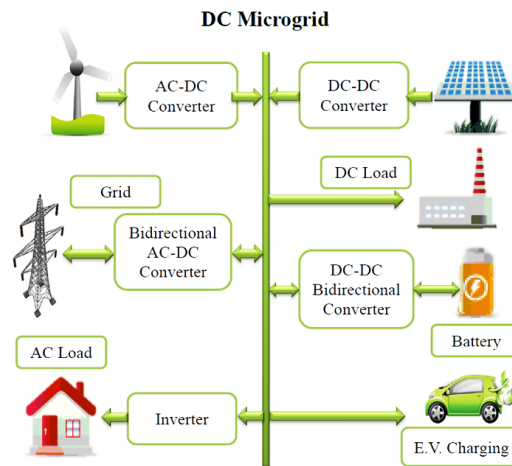


Fig. 1: The common structure of a DC microgrid

This paper aims to provide a review on various load sharing strategies available in the scientific literature for a DC microgrid. Considering the control strategy, the problem of load sharing can be minimized by active load sharing method and passive load sharing method [15], [16]. Active load sharing is effective for load sharing and voltage restoration but requires a high-bandwidth communication link and is not flexible or modular. As microgrids and distributed generators increase, a higher-bandwidth link is needed. Droop control has a lower load sharing capacity but doesn't require a communication link and doesn't affect system modularity [17].

II. REVIEW METHODOLOGY

Wherever The DC microgrid integrates distributed generation and electrical loads using DC/DC converters [13]. Operating converters in parallel enhances system reliability and flexibility [18]. Simultaneously, it also presents challenges with distributing the load among converters [19], [20]. Load sharing is the process of distributing electric current among multiple sources to achieve a more balanced and efficient use of energy supplies. When converters operate in parallel, it is crucial for each converter to share the load according to its ratings. Failure to do so can result in the flow of circulating current between converters. This leads to the overloading of one converter and the underloading of another. Regrettably, this results in additional losses, heat generation, larger size, and higher ratings of converters [21]. Thus, it is strongly advised to evenly share the load current among all the converters in the DC microgrid. Furthermore, it is crucial to guarantee that the load voltage stays within precise boundaries, usually within a tolerance of $\pm 5\%$ [22].

To mitigate the load sharing error, the control methods can be categorized into two primary classifications: active load sharing and passive load sharing [14]. Passive load sharing is also known as droop control. Load sharing and Voltage regulation are the primary control of the hierarchical control strategy which can be performed with communication or without communication links [23]. Figure 2 represents various load sharing strategies used in DC microgrid.

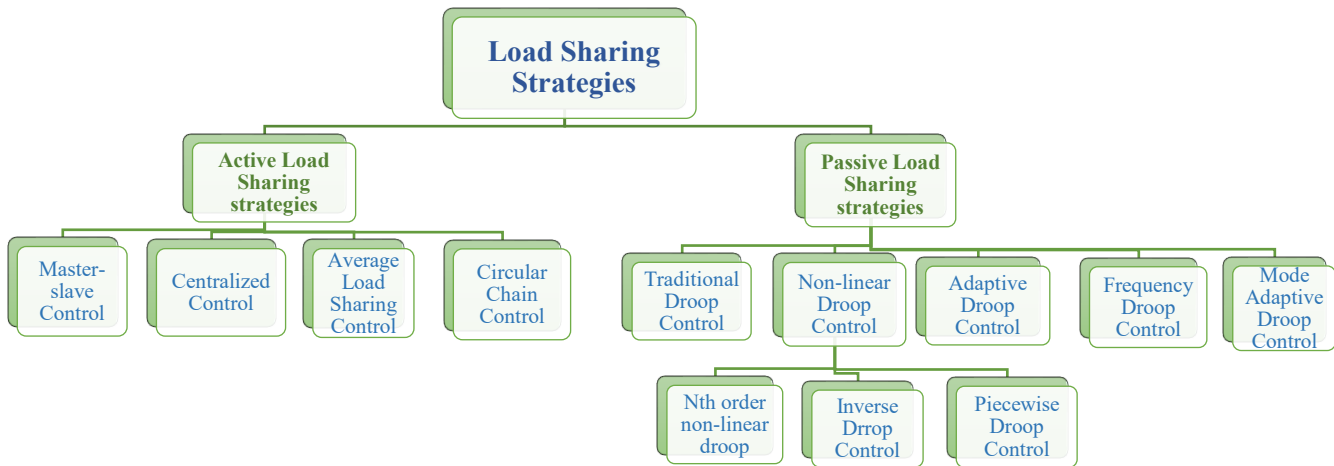


Fig. 2: Various load sharing strategies used in DC microgrid

Communication encounters challenges such as delays in transmitting information, loss of data, and cost-related concerns. It negatively impacts system scalability, reliability, flexibility, modularity, and expandability. By utilizing no communication methods with decentralized control techniques, one can effectively mitigate the drawbacks associated with communication [24]. They provide benefits like easy implementation, and affordability, as well as modularity, flexibility, expandability, and reliability.

A. Active load sharing methods:

The most common active load-sharing methods consist of master-slave control, centralized control, average current sharing method, and circular chain control [25], [26].

a) Master-slave control:

The Master-Slave control strategy involves selecting one converter as the master control module with the responsibility of establishing the DC bus voltage. Subsequently, the remaining converters are configured as slave converters functioning with current control mode. One module is voltage control, which guarantees effective regulation of voltage. Another module is current control, which allows for equal distribution of current among the converters [27]. Figure 3 demonstrates the block diagram of master-slave control.

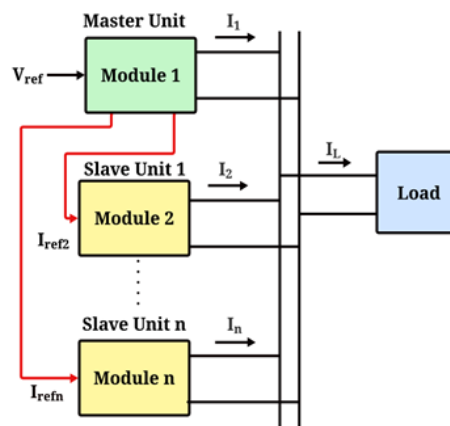


Fig. 3: block diagram of master-slave control

The transmission of signals requires communication network with high bandwidth, resulting in the system's lack of reliability. The master-slave control is specifically used in small-scale microgrids, such as electric aircraft, DC server systems, ships etc. [28].

b) Centralized control:

Reference [29] presents a novel two-level control scheme designed to achieve precise load sharing and suitable voltage regulation in islanded DC microgrid. The proposed scheme utilizes a P-V droop method in primary control to guarantee precise load sharing among Distributed Energy Resources (DERs). And the centralized secondary control aims to eliminate voltage deviation and maintain the constant voltage. The paper introduces a new control strategy for isolated DC microgrids in buildings as described in [30]. This strategy effectively eliminates voltage fluctuations in the DC bus caused by unpredictable disturbances in the system. Figure 4 demonstrates the block diagram of centralized control. Centralized control requires a high-bandwidth communication network to communicate secondary control with a central controller.

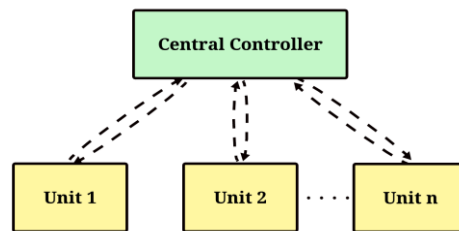


Fig. 4: block diagram of centralized control

c) Average load sharing control:

The article [31] presents the average current sharing (ACS) scheme. The ACS scheme configuration calculates the current as the mean of all current values. The droop gain multiplies it into a voltage signal and connects it to the positive input of the operational amplifier. As a result of the connection between the current sharing bus and each signal conditioner through resistor, and bus will exhibit an average voltage. By selecting appropriate impedances for the operational amplifier, it is possible to eliminate the droop voltage drop. Thereby output voltage can be restored. Nevertheless, it is susceptible to noise in long-distance scenarios. Hence, the digital current sharing scheme (DACS) is implemented. The functionality of DACS is closely tied to the communication network. Average current control is a method that operates by comparing the average current of the inductor to the desired set current.

d) Circular chain control (3C):

The circular chain control method was previously proposed to improve the system's reliability and resilience. This method created a control ring by extracting the current reference of one module from another. Figure 5 represents the example of circular chain control. To form a ring, the current reference of the first unit is derived from the last unit. The system's circular communication structure enhances its fault detection and isolation capability [25].

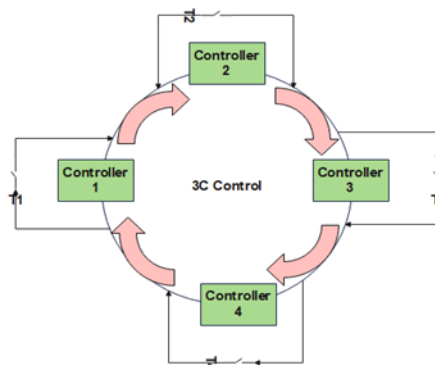


Fig. 5: Circular chain control

B. Passive load sharing methods:

As stated earlier, the majority of the load sharing methods in paralleled DC/DC converters depend on high-bandwidth communication networks. Nevertheless, in DC microgrids, the integration of Distributed Energy Resources (DERs) and loads to the point of common coupling (PCC) could make it unfeasible or costly to employ a high-capacity communication network, primarily due to concerns regarding data dependability and investment costs. Therefore, droop control method has gained significant attention [32].

a) Traditional droop control:

The Droop control is extensively utilized in the parallel operation of power modules, as well as in AC and DC microgrids [33]. Previously, In the domain of analog circuit design and control, droop control was regarded as an adaptive voltage positioning (AVP) technique [32]. An important benefit of droop control is its capacity to achieve load sharing among parallel converters without requiring dedicated communication links. This allows the implementation of decentralized system control.

In widely used voltage-current droop (V-I droop) method, each converter adjusts its output voltage in response to variations in output current. Therefore, it is possible to achieve load sharing in a steady state.

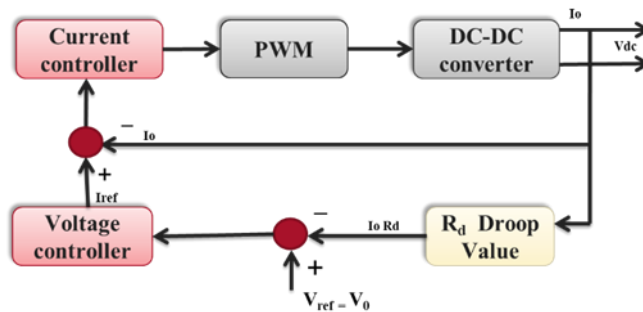


Fig. 6: The general structure of droop control technique

Figure 6 illustrates the general structure of droop control technique. The Proportional Integral (PI) controllers are used to regulate the voltages on the Common DC bus and the converter current. The external voltage controller compares the output voltage value to the desired reference value and sends a reference current value to the internal current control. The inner control mechanism compares the reference value to the inductor current and produces signals accordingly. The PWM block then compares these signals and sends on-off signals to the converter switch. A traditional droop-controlled system employs a constant droop gain over the entire DC-terminal voltage range.

The droop gain values have a substantial impact on the stability of the microgrid, the accuracy of voltage regulation, and the precision of load sharing. The primary drawbacks of traditional droop control are enumerated in [14], [34], [35]. A traditional droop control system has a predetermined and unchanging droop value. It does not consider the load dynamics that can result in failure following a significant or rapid change in load. The system's inability to initiate a black start-up after a collapse necessitates the implementation of specific measures for restoring the system.

• Trade-off in traditional droop control technique:

According to the block diagram in figure 6, the DC bus voltage can be calculated using equation (1).

$$V_{dci} = V_{ref} - I_{oi} R_{di} \tag{1}$$

Where, V_{dci} is DC bus voltage, V_{ref} is the no load or reference voltage, I_{oi} is the output current and R_{di} is the droop resistance of i th converter. Hence, based on the provided equation, it is evident that increasing the droop value will result in a linear decrease or deviation of the output voltage caused by the droop resistance. Figure 7 demonstrates that when the current value is low, the terminal voltage is close to the no-load voltage (V_0). However, as the current being drawn from the load increases, the voltage at the terminal decreases linearly. The small droop value provides excellent voltage regulation but lacks sufficient load sharing capability. If one selects a large droop value, load sharing will be favorable, but voltage regulation will be subpar. Hence, there is always a trade-off between load sharing accuracy and voltage regulation in traditional droop technique. Additionally, the cable resistance is also crucial in

droop control. Every cable linking the converter to the common bus terminal possesses a distinct cable resistance. The cable resistance is also regarded as being connected in series with the droop resistance. Thus, the resistance of the cable not only reduces the output voltage according to equation 2, but also increases the load sharing error (Error).

$$V_{oi} = V_{ref} - I_{oi} R_{di} - I_{oi} R_{ci} \tag{2}$$

The ratio of current drawn by each converter can be given as:

$$\frac{I_{o1}}{I_{o2}} = \frac{R_{d2} + R_{c2}}{R_{d1} + R_{c1}} \tag{3}$$

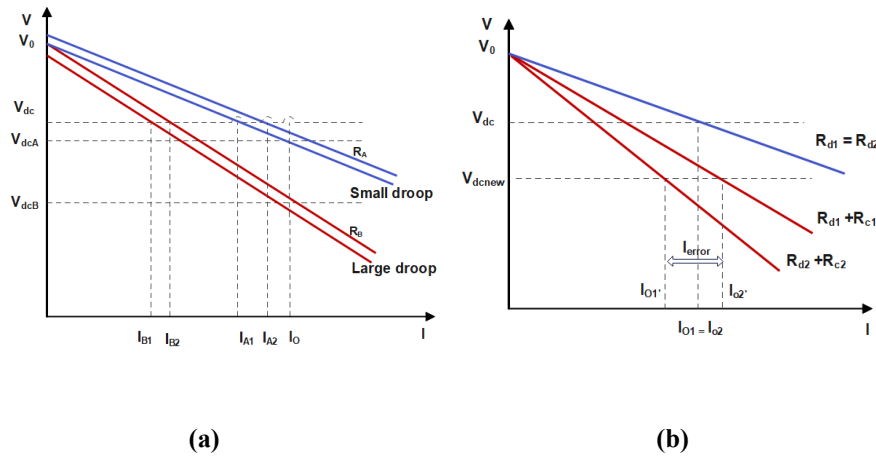


Fig. 7: Impact of droop resistance(a) and line resistance (b) on voltage regulation and load sharing [36]

b) Non-linear droop control:

In [37], A novel current-limiting droop controller is proposed for paralleled DC-DC boost converters in a DC microgrid. The controller ensures that each converter has an inherent current-limiting property, regardless of the load type or magnitude variations. It provides accurate power sharing, tight voltage regulation, and closed-loop stability for multiple paralleled boost converters with a current limit. In the nonlinear droop method [38], the authors analyze cable resistance impact and propose a nonlinear droop method that increases droop resistance with converter output current, preserving traditional droop control advantages. It evaluates and compares second-order droop functions.

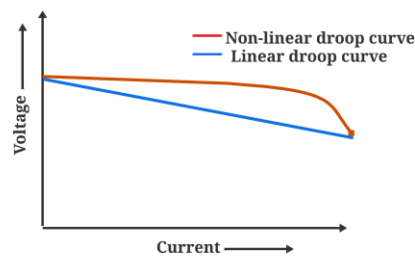


Fig. 8: formation of non-linear droop curve [37]

In [39], different non-linear droop control methods are proposed for smart grid to improve load sharing accuracy and voltage regulation in DC microgrid. These methods are High Droop Gain (HDG), Polynomial Droop Curve (PDC), and Polynomial Droop Curve with Voltage Compensation (PDCVC). These decentralized methods require only local information, making them easy to implement and improving system reliability. Performance analysis clearly illustrates the superiority of these methods compared to traditional approaches in various operating conditions. Nevertheless, there is still a compromise between maintaining stable voltage and achieving equal distribution of current. Inadequate regulation under light load conditions is seen in the method, Incorrect selection of the droop curve may lead to stability issues.

c) *Nth order non-linear droop control:*

In [40], The research paper examines the design of non-linear droop curve for DC distribution. The method mainly focuses on load sharing, voltage regulation, efficiency, and stability of the system. It presents a generic polynomial expression to unify droop equations, analyzes the impact of droop constant on efficiency, and models converter output impedance for stability. The analysis verified that nonlinear droop is fully distributed and requires local information. A higher-order polynomial exhibits superior performance under heavy load conditions. The unresolved problem between load sharing and voltage regulation persists, and the matter of circulating current has yet to be tackled.

d) *Inverse droop control:*

In [41],[42], the research work introduces a decentralized inverse-droop control method for input-series-output-parallel DC/DC converters, aimed at enhancing the system's modularity, reliability, and flexibility. The control achieves power sharing, and output voltage regulation, and is stable despite input voltage variations. As shown in Figure 9, the proposed inverse-droop mechanism causes the output voltage reference to increase as the load becomes more substantial.

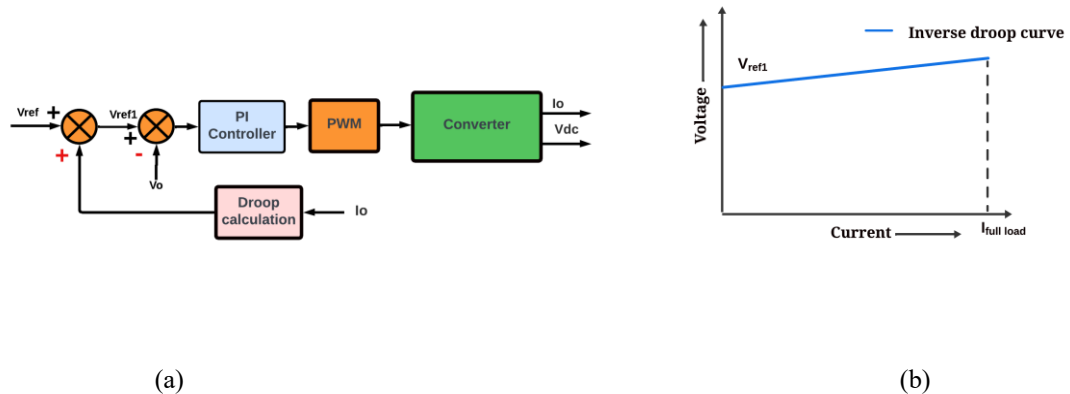


Fig. 9: Inverse-droop control concept (a), and Inverse droop curve (b) [40]

In the inverse droop control methods, positive feedback may produce an unstable system and less output voltage accuracy. So cannot be used where précised voltage regulation is required.

e) *Piecewise droop control:*

In [43],[44],[45], using piecewise droop control, the droop curves are divided into small segments. Once the load surpasses a specific limit, the system initiates the utilization of a greater droop resistance. Figure 10 illustrates how this approach employs different inclinations to minimize the load sharing error resulting from voltage measurement inaccuracies.

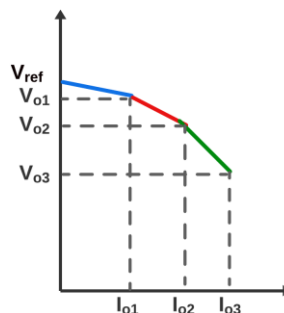


Fig. 10: Piece-wise droop curve [44]

In [46], the General piecewise droop is introduced. In this paper, different piecewise droop control methods have been implemented for DC microgrid. These strategies allow for the design of systems with a large number of possible configurations, as well as load sharing in a way that adapts to changing conditions. This is accomplished by creating droop curves that vary in a segmented manner according to the load regions. In the Piecewise droop control method, the switching between different modes is abrupt. Power converters may experience abrupt changes in output resistance, which can result in unwanted transients and oscillations.

The aforementioned study discovered that nonlinear droop exhibited superior performance compared to traditional droop control technique. Nevertheless, they neglected to take into account the influence of droop control on the efficiency of the system [47]. According to [48], the implementation of nonlinear droop control allows for the optimization of the droop gain. This is achieved by increasing the gain at heavy loads and decreasing it at lighter load conditions. Nonlinear controllers, however, introduce nonlinearity into the control system.

f) Adaptive droop control:

Various adaptive droop control methods suggest the use of an adjustable droop coefficient instead of a fixed droop coefficient, which is typically used in traditional droop control technique. Paper [21] proposes an adaptive droop control algorithm and a distributed secondary controller to improve load sharing accuracy. It suppresses the circulating current and ensures accurate load sharing. It uses mathematical calculations to estimate line resistances and adjust droop parameters.

In paper [49], The proportional droop index (PDI) algorithm is used with droop shifting to improve load sharing performance in low-voltage DC microgrid. This method calculates adaptive virtual resistance, and reduces the trade-off between load sharing and voltage deviation. In contrast with the above droop index control, a new droop index method has been observed in [50], which includes variation in input parameters. This method has a good response with variations in supply voltage, variation in load, and variation in line resistance.

In [51], a methodology is proposed to estimate the resistance of a line. This involves increasing the voltage reference by an amount equal to the voltage drop caused by the line resistance. As a result, load sharing is equalized and voltage regulation is improved. This method operates independently of a communication network and relies solely on local parameters.

In [52], the proposed control technique has used MOSFET as a switching device which gives a faster response. Circulating current, power loss is reduced and voltage regulation is improved by this method. Paper [53] proposes an adaptive droop controller that addresses the limitations of traditional droop control. The controller uses primary load sharing loops to adjust droop parameters. The algorithm is tested for variation in input parameters and loading conditions, showing good performance compared to traditional control. Furthermore, the secondary loop adjusts the droop lines to effectively eliminate any deviation in the bus voltage. In [54], a research paper proposes a dual reference-based control strategy and virtual resistance-based droop technique for improved load sharing and voltage regulation.

The adaptive droop control method is characterized by its enhanced flexibility and applicability, as well as its ability to minimize voltage deviations and load sharing errors [48]. The problem of circulating current is also solved to a great extent using many adaptive droop control methods.

g) Frequency droop control:

In [55], The paper suggests an adaptive droop controller that utilizes superimposed frequency to enhance load sharing accuracy and voltage regulation, without the need for additional communication systems. The secondary controller autonomously calculates and offsets the decrease in voltage caused by the droop controller. This method faces three main issues: instability in load variation due to dominant pole location, system loading limitations because of reactive power transfer, and poor voltage quality from AC voltage injection. To address the above issues, an adaptive Voltage Coupling Gain (AVCG) and Adaptive Amplitude of the Injected AC Voltage (AAIV) are introduced in [56]. These two methods stabilize and improve the

loading condition of a DC microgrid, while also enhancing system voltage quality by limiting AC voltage amplitude. However, the frequency injection method introduces a ripple in output.

h) Mode adaptive droop control (MADC):

In [57] The study proposes a mode adaptive droop control strategy that includes PV, wind, and energy storage systems. This strategy uses a hysteresis feature to switch between voltage control by the Renewable Energy Source and the Battery Energy Storage in the islanded microgrid. all the grid components are working either in droop control mode or constant power mode, Mode I corresponds to the utility's droop control mode, while mode II represents energy storage units in droop control mode, and mode III corresponds to DG units in droop control mode.

III. OVERVIEW OF VARIOUS LOAD SHARING STRATEGIES

Table 1 demonstrates the overview of different active load sharing strategies and Table 2 demonstrates the overview of different passive load sharing strategies.

Table 1. Comparison of different active load sharing strategies.

| Active load sharing strategies | Features | Disadvantages | Is the circulating current problem examined? |
|-----------------------------------|--|---|--|
| Master-slave control [27] | Master control is used for voltage regulation and slave is used for current sharing. | <ul style="list-style-type: none"> • It needs a high bandwidth communication network, which leads to the unreliability of the system. • It applies to small-scale microgrids only • Limitation of scalability and flexibility. | No |
| Centralized control [29], [30] | A centralized secondary scheme is proposed for resolving voltage deviations caused by the primary controller. Additionally, load sharing is accomplished through the primary controller. | <ul style="list-style-type: none"> • A high-bandwidth communication network is required. • The secondary controller produces a time delay which affects the system stability. • Require an additional controller and communication network, resulting in an increased total cost of the system. • Affected from single-point failure. • Low reliability. • poor plug-and-play capability. • limitation in scalability. | No |
| Average load sharing control [31] | The current is determined by calculating the mean of all current values. This means current is then transformed into a voltage signal and subsequently amplified by the droop gain. | <ul style="list-style-type: none"> • With the growing complexity of the power system and loads, it became evident that average current control also has its limitations, including restrictions on switching frequency [25]. • For long-distance applications, the common bus carrying analog signals may be susceptible to noise. DACS needs communication which created the problem of data latency and data drop. | No |
| Circular chain control (3C) [25] | This method establishes a control loop by transferring the current reference between different modules. | <ul style="list-style-type: none"> • It needs continuous communication between converters. • It may cause the problem of data latency and data drop. | No |

Table 2. Comparison of different passive load sharing strategies.

| Passive load sharing strategies | Features | Disadvantages | Is the circulating current problem examined? |
|--|---|---|--|
| Traditional droop control [32],[33] | With droop control, load sharing among paralleled power sources becomes possible without the need for dedicated communication links. This allows for decentralized and reliable system control. | <ul style="list-style-type: none"> • Poor transient performance. • Poor performance during large or fast load changes. • Difficulty in achieving precise load sharing among the converters caused by uncertainties in output impedance. • Not suitable for nonlinear loads as it fails to consider harmonic currents. | No |
| Non-linear droop [37],[38],[39] | The droop resistance varies with the converter's output current, and its value rises as the converter's output current increases. | <ul style="list-style-type: none"> • Under light load conditions, it demonstrates excellent voltage regulation. However, when subjected to heavy loads, the voltage regulation tends to be inadequate. • The impact of line resistance is not eliminated. | Yes |
| Nth-order nonlinear droop control [40] | It offers a generic polynomial expression to simplify different droop equations, thus reducing the influence of sensors and cables. | <ul style="list-style-type: none"> • Trade-off between voltage regulation and voltage regulation is still present. • Only $m = 1$, large n, $n=5$ gives better performance at heavy load. | No |
| Inverse droop control [41],[42] | The voltage reference increases as the load increases. | <ul style="list-style-type: none"> • The inverse droop control increases system complexity and nonlinearity, particularly in large systems. A negative droop means it is an inverse droop that suffers from a problem of stability due to positive feedback. | No |
| Piecewise droop control [43],[44],[45] | In Piecewise droop control, the droop curves are splatted into small segments. The system adjusts its droop resistance when the load exceeds a certain threshold value. | <ul style="list-style-type: none"> • The transition between different modes is sudden. • Power converters can sometimes experience unexpected transients and oscillations due to sudden changes in output resistance. • There are still issues with load sharing at light load and voltage regulation at heavy load. • Dividing the segments into smaller sections can result in more accurate design and improved control performance, although it may make the design process more complex. | Yes |
| Adaptive droop control [21],[49] | The mathematical equations are used to calculate droop resistances. | <ul style="list-style-type: none"> • Complex calculations are required for the adjustment of the droop parameter. • Sometimes it needs a secondary controller for voltage restoration. • So, secondary controllers need extra communication lines. | Yes |
| Frequency droop control [55],[56] | An AC voltage is injected into the main DC system. The frequency of the injected voltage is proportional to the output of the corresponding converter. | <ul style="list-style-type: none"> • A frequency injection method introduces a ripple in output. • instability in load variation due to dominant pole location, system loading limitations due to reactive power transfer, and poor voltage quality due to AC voltage injection. | No |
| Mode adaptive droop control [57] | Droop control is utilized for adjusting voltage ranges in the utility grid and DERs. | <ul style="list-style-type: none"> • It is designed based on the assumption that all DERs measure equal bus voltages, neglecting the voltage drops caused by the line resistances. | No |

IV. CONCLUSION

This paper provides through review of various load sharing strategies used in DC microgrid. The cited literature mainly employs active or passive load sharing strategies. Both strategies have their advantages and disadvantages. Active load sharing strategies have good load sharing accuracy and voltage regulation. However, these strategies either require an additional component, increase the number of devices, or require high-bandwidth communication links so that each converter is aware of the state of the others. Communication diminishes the reliability and flexibility of the system. Microgrid plug-and-play becomes less common as communication lines grow longer. Some methods employ Low-bandwidth Communication networks, which results in data dependency, latency, and system delay.

Based on current research on droop control in DC microgrids, it has been found that most enhanced droop controls are primarily designed to address load sharing, while only a few of them can effectively handle both load sharing and voltage regulation at the primary level. Increasing secondary control can compensate for the voltage drop induced by droop control. Once more, it adds complexity to the control design. Nonlinear droop exhibits strong current sharing capabilities, especially under high load conditions, but its voltage regulation is inadequate.

Circulating current can occur even with minor voltage fluctuations in the converter output. Most of the work focuses on improving voltage regulation and load sharing. Few efforts are made to reduce the circulating current. The majority of DC microgrids use adaptive droop to reduce the amount of circulating current.

Several additional studies have been carried out to control the voltage of the DC bus and ensure proper distribution of the load, considering factors such as load fluctuations and cable resistance. However, input variables like input voltage and current from the source side have not been taken into consideration. This demonstrates that certain methods do not consider fluctuations in input voltage and only focus on changes in the load.

Many of the methods described above are based on a single-load DC microgrid. Their application in microgrids with multiple loads at different locations has not been considered. Coordination of DGs for voltage regulation and current sharing in multi-load microgrids is challenging. When loads are distributed across multiple locations, distribution line impedances are likely to be unequal, affecting load voltage, current, and power regardless of source number or type. Source and load connections are determined by power demand, load, and distributed generation locations, as well as distance. Different line impedances, configurations, and spreading locations cause voltage differences between loads. A proper compensation method is required to precisely regulate the voltage and distribute current among distributed generations.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

FUNDING SOURCES

The authors received no financial support for the research, authorship, and/or publication of this article.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of the Gujarat Technological University – Ahmedabad (India) for providing research facilities.

REFERENCES:

- [1] S. R. Bull, "Renewable energy today and tomorrow," *Proceedings of the IEEE*, vol. 89, no. 8, pp. 1216–1226, 2001, doi: 10.1109/5.940290.
- [2] N. Ertugrul and D. Abbott, "DC is the Future [Point of View]," *Proceedings of the IEEE*, vol. 108, no. 5, pp. 615–624, 2020, doi: 10.1109/JPROC.2020.2982707.
- [3] V. S. K. Murthy Balijepalli, S. A. Khaparde, and C. V. Dobariya, "Deployment of MicroGrids in India," *IEEE PES General Meeting, PES 2010*, pp. 1–7, 2010, doi: 10.1109/PES.2010.5589956.
- [4] S. Chandak and P. K. Rout, "The implementation framework of a microgrid: A review," *Int J Energy Res*, vol. 45, no. 3, pp. 3523–3547, 2021, doi: 10.1002/er.6064.
- [5] F. S. Al-ismail and S. Member, "DC Microgrid Planning, Operation, and Control: A Comprehensive Review," vol. 9, 2021, doi: 10.1109/ACCESS.2021.3062840.
- [6] P. Hategekimana, A. Junyent-Ferré, E. Ntagwirumugara, and J. M. R. Bernuz, "Improved methods for controlling interconnected DC microgrids in rural villages," *AIMS Energy*, vol. 12, no. 1, pp. 214–234, 2024, doi: 10.3934/energy.2024010.
- [7] R. Majumder, "Modeling, Stability Analysis and Control of Microgrid," *Control*, no. February, p. 182, 2010.
- [8] S. Boudoudouh and M. Maaroufi, "Renewable Energy Sources Integration and Control in Railway Microgrid," *IEEE Trans Ind Appl*, vol. 55, no. 2, pp. 2045–2052, 2019, doi: 10.1109/TIA.2018.2878143.
- [9] D. Kumar, F. Zare, and A. Ghosh, "DC Microgrid Technology: System Architectures, AC Grid Interfaces, Grounding Schemes, Power Quality, Communication Networks, Applications, and Standardizations Aspects," *IEEE Access*, vol. 5, pp. 12230–12256, 2017, doi: 10.1109/ACCESS.2017.2705914.
- [10] K. A. Jadav, H. M. Karkar, and I. N. Trivedi, "A Review of Microgrid Architectures and Control Strategy," *Journal of The Institution of Engineers (India): Series B*, vol. 98, no. 6, pp. 591–598, 2017, doi: 10.1007/s40031-017-0287-3.
- [11] K. Jithin, G. Student Member, P. P. Haridev, N. Mayadevi, R. Hari Kumar, and V. P. Mini, "A Review on Challenges in DC Microgrid Planning and Implementation," 2022, doi: 10.35833/MPCE.2022.000053.
- [12] F. Zhang et al., "Advantages and challenges of DC microgrid for commercial building: A case study from Xiamen University DC microgrid," 2015 IEEE 1st International Conference on Direct Current Microgrids, ICDCM 2015, pp. 355–358, 2015, doi: 10.1109/ICDCM.2015.7152068.
- [13] X. Lu et al., "Hierarchical Control of Parallel AC-DC Converter Interfaces for Hybrid Microgrids," pp. 1–10, 2013.
- [14] A. Bidram and A. Davoudi, "Hierarchical structure of microgrids control system," *IEEE Trans Smart Grid*, vol. 3, no. 4, pp. 1963–1976, 2012, doi: 10.1109/TSG.2012.2197425.
- [15] U. B. Tayab, M. A. Bin Roslan, L. J. Hwai, and M. Kashif, "A review of droop control techniques for microgrid," *Renewable and Sustainable Energy Reviews*, vol. 76, no. November 2016, pp. 717–727, 2017, doi: 10.1016/j.rser.2017.03.028.
- [16] S. E. Mhankale and A. R. Thorat, "Droop Control Strategies of DC Microgrid: A Review," *Proceedings of the 2018 International Conference on Current Trends towards Converging Technologies, ICCTCT 2018*, 2018, doi: 10.1109/ICCTCT.2018.8550854.
- [17] E. Pathan, A. A. Bakar, M. H. Khan, M. Asad, and H. Arshad, "Multiloop low bandwidth communication-based power sharing control for microgrids," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 21, no. 2, pp. 682–690, 2020, doi: 10.11591/ijeecs.v21.i2.pp682-690.
- [18] A. Mohd, E. Ortjohann, D. Morton, and O. Omari, "Review of control techniques for inverters parallel operation," *Electric Power Systems Research*, vol. 80, no. 12, pp. 1477–1487, Dec. 2010. doi: 10.1016/j.epsr.2010.06.009.
- [19] A. Ashok Kumar and N. Amutha Prabha, "A comprehensive review of DC microgrid in market segments and control technique," *Heliyon*, vol. 8, no. 11. Elsevier Ltd, Nov. 01, 2022. doi: 10.1016/j.heliyon.2022.e11694.
- [20] J. M. Guerrero, P. C. Loh, T. L. Lee, and M. Chandorkar, "Advanced control architectures for intelligent microgrids Part II: Power quality, energy storage, and AC/DC microgrids," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1263–1270, 2013, doi: 10.1109/TIE.2012.2196889.

- [21] N. Ghanbari and S. Bhattacharya, "Adaptive Droop Control Method for Suppressing Circulating Currents in DC Microgrids," *IEEE Open Access Journal of Power and Energy*, vol. 7, no. January, pp. 100–110, 2020, doi: 10.1109/oajpe.2020.2974940.
- [22] M. A. Setiawan, A. Abu-Siada, and F. Shahnia, "A New Technique for Simultaneous Load Current Sharing and Voltage Regulation in DC Microgrids," *IEEE Trans Industr Inform*, vol. 14, no. 4, pp. 1403–1414, Apr. 2018, doi: 10.1109/TII.2017.2761914.
- [23] F. Gao, R. Kang, J. Cao, and T. Yang, "Primary and secondary control in DC microgrids: a review," *Journal of Modern Power Systems and Clean Energy*, vol. 7, no. 2, pp. 227–242, 2019, doi: 10.1007/s40565-018-0466-5.
- [24] A. K. Sahoo, K. Mahmud, M. Crittenden, J. Ravishankar, S. Padmanaban, and F. Blaabjerg, "Communication-Less Primary and Secondary Control in Inverter-Interfaced AC Microgrid: An Overview," *IEEE J Emerg Sel Top Power Electron*, vol. 9, no. 5, pp. 5164–5182, Feb. 2020, doi: 10.1109/jestpe.2020.2974046.
- [25] J. Kumar, A. Agarwal, and V. Agarwal, "A review on overall control of DC microgrids," *Journal of Energy Storage*, vol. 21. Elsevier Ltd, pp. 113–138, Feb. 01, 2019. doi: 10.1016/j.est.2018.11.013.
- [26] J. Peng, B. Fan, J. Duan, Q. Yang, and W. Liu, "Adaptive decentralized output-constrained control of single-bus DC microgrids," *IEEE/CAA Journal of Automatica Sinica*, vol. 6, no. 2, pp. 424–432, Mar. 2019, doi: 10.1109/JAS.2019.1911387.
- [27] J. Rajagopalan, K. Zing, Y. Guo, F. C. Lee, and B. Manners, "Modeling and Dynamic Analysis of Paralleled dc/dc Converters with Master-Slave Current Sharing Control," 1996. [Online]. Available: <https://ntrs.nasa.gov/search.jsp?R=19970022703>
- [28] T. Dragičević, X. Lu, J. C. Vasquez, and J. M. Guerrero, "DC Microgrids - Part II: A Review of Power Architectures, Applications, and Standardization Issues," *IEEE Transactions on Power Electronics*, vol. 31, no. 5. Institute of Electrical and Electronics Engineers Inc., pp. 3528–3549, May 01, 2016. doi: 10.1109/TPEL.2015.2464277.
- [29] M. Baharizadeh, M. S. Golsorkhi, M. Shahparasti, and M. Savaghebi, "A Two-Layer Control Scheme Based on P-V Droop Characteristic for Accurate Power Sharing and Voltage Regulation in DC Microgrids," *IEEE Trans Smart Grid*, vol. 12, no. 4, pp. 2776–2787, Jul. 2021, doi: 10.1109/TSG.2021.3060074.
- [30] Z. Yi, X. Zhao, D. Shi, J. Duan, Y. Xiang, and Z. Wang, "Accurate Power Sharing and Synthetic Inertia Control for DC Building Microgrids with Guaranteed Performance," *IEEE Access*, vol. 7, pp. 63698–63708, 2019, doi: 10.1109/ACCESS.2019.2915046.
- [31] P. H. Huang, P. C. Liu, W. Xiao, and M. S. el Moursi, "A Novel Droop-Based Average Voltage Sharing Control Strategy for DC Microgrids," *IEEE Trans Smart Grid*, vol. 6, no. 3, pp. 1096–1106, May 2015, doi: 10.1109/TSG.2014.2357179.
- [32] L. Meng et al., "Review on Control of DC Microgrids and Multiple Microgrid Clusters," *IEEE J Emerg Sel Top Power Electron*, vol. 5, no. 3, pp. 928–948, Sep. 2017, doi: 10.1109/JESTPE.2017.2690219.
- [33] J. W. Kim, H. S. Choi, and B. H. Cho, "A novel droop method for converter parallel operation," *IEEE Trans Power Electron*, vol. 17, no. 1, pp. 25–32, 2002, doi: 10.1109/63.988666.
- [34] U. B. Tayab, M. A. bin Roslan, L. J. Hwai, and M. Kashif, "A review of droop control techniques for microgrid," *Renewable and Sustainable Energy Reviews*, vol. 76, no. November 2016, pp. 717–727, 2017, doi: 10.1016/j.rser.2017.03.028.
- [35] D. E. Olivares et al., "Trends in microgrid control," *IEEE Trans Smart Grid*, vol. 5, no. 4, pp. 1905–1919, 2014, doi: 10.1109/TSG.2013.2295514.
- [36] B. S. Kala et al., "CIRCULATING CURRENT MINIMIZATION IN LOW-VOLTAGE DC MICROGRID BASED ON DROOP CONTROL STRATEGY." [Online]. Available: <http://ijrar.com/>
- [37] A. C. Braitor, G. C. Konstantopoulos, and V. Kadiramanathan, "Current-Limiting Droop Control Design and Stability Analysis for Paralleled Boost Converters in DC Microgrids," *IEEE Transactions on Control Systems Technology*, vol. 29, no. 1, pp. 385–394, Jan. 2021, doi: 10.1109/TCST.2019.2951092.
- [38] F. Chen, R. Burgos, D. Boroyevich, and W. Zhang, "A nonlinear droop method to improve voltage regulation and load sharing in DC systems," in 2015 IEEE 1st International Conference on Direct Current Microgrids, ICDCM 2015, Institute of Electrical and Electronics Engineers Inc., Jul. 2015, pp. 45–50. doi: 10.1109/ICDCM.2015.7152008.

- [39] P. Prabhakaran, Y. Goyal, and V. Agarwal, "Novel nonlinear droop control techniques to overcome the load sharing and voltage regulation issues in DC Microgrid," *IEEE Trans Power Electron*, vol. 33, no. 5, pp. 4477–4487, May 2018, doi: 10.1109/TPEL.2017.2723045.
- [40] F. Chen, R. Burgos, D. Boroyevich, J. C. Vasquez, and J. M. Guerrero, "Investigation of Nonlinear Droop Control in DC Power Distribution Systems: Load Sharing, Voltage Regulation, Efficiency, and Stability," *IEEE Trans Power Electron*, vol. 34, no. 10, pp. 9407–9421, Oct. 2019, doi: 10.1109/TPEL.2019.2893686.
- [41] G. Xu, D. Sha, and X. Liao, "Decentralized inverse-droop control for input-series-output-parallel DC-DC Converters," *IEEE Trans Power Electron*, vol. 30, no. 9, pp. 4621–4625, 2015, doi: 10.1109/TPEL.2015.2396898.
- [42] L. Shu, W. Chen, and X. Jiang, "Decentralized Control for Fully Modular Input-Series Output-Parallel (ISOP) Inverter System Based on the Active Power Inverse-Droop Method," *IEEE Trans Power Electron*, vol. 33, no. 9, pp. 7521–7530, 2018, doi: 10.1109/TPEL.2017.2773559.
- [43] T. Hailu and J. A. Ferreira, "Piece-wise Linear Droop Control For Load Sharing In Low Voltage DC Distribution Grid."
- [44] Y. Lin and W. Xiao, "Novel Piecewise Linear Formation of Droop Strategy for DC Microgrid," *IEEE Trans Smart Grid*, vol. 10, no. 6, pp. 6747–6755, Nov. 2019, doi: 10.1109/TSG.2019.2911013.
- [45] P. Zhao, Z. Liu, and J. Liu, "An Adaptive Discrete Piecewise Droop Control in DC Microgrids," *IEEE Trans Smart Grid*, p. 1, 2023, doi: 10.1109/TSG.2023.3302688.
- [46] S. Liu, J. Zheng, Z. Li, and X. Liu, "A general piecewise droop design method for DC microgrid," *International Journal of Electronics*, vol. 108, no. 5, pp. 758–776, 2021, doi: 10.1080/00207217.2020.1818839.
- [47] P. Zafari, A. Zangeneh, M. Moradzadeh, A. Ghafouri, and M. A. Parazdeh, "Various Droop Control Strategies in Microgrids," in *Power Systems*, Springer Verlag, 2020, pp. 527–554. doi: 10.1007/978-3-030-23723-3_22.
- [48] Z. Shuai, J. Fang, F. Ning, and Z. J. Shen, "Hierarchical structure and bus voltage control of DC microgrid," *Renewable and Sustainable Energy Reviews*, vol. 82. Elsevier Ltd, pp. 3670–3682, Feb. 01, 2018. doi: 10.1016/j.rser.2017.10.096.
- [49] Augustine, Sijo, Mahesh K. Mishra, and N. Lakshminarasamma. "Adaptive droop control strategy for load sharing and circulating current minimization in low-voltage standalone DC microgrid." *IEEE Transactions on Sustainable Energy* 6.1 (2014): 132-141.
- [50] P. K. Gorijeevaram Reddy, S. Dasarathan, and V. Krishnasamy, "Investigation of adaptive droop control applied to low-voltage DC microgrid," *Energies (Basel)*, vol. 14, no. 17, Sep. 2021, doi: 10.3390/en14175356.
- [51] S. Chaturvedi and D. M. Fulwani, "Equal Load Sharing in DC Microgrid Using Line Resistance Estimation," in *Lecture Notes in Electrical Engineering*, Springer, 2020, pp. 87–96. doi: 10.1007/978-981-15-0226-2_7.
- [52] A. Mehta, A. Rawat, and P. Chauhan, "Lecture Notes in Electrical Engineering 604 Advances in Control Systems and its Infrastructure." [Online]. Available: <http://www.springer.com/series/7818>.
- [53] M. A. Ghalib, E. G. Shehat, J. Thomas, and R. M. Mostafa, "Adaptive droop control for high-performance operation in low-voltage DC microgrids," *Electrical Engineering*, vol. 101, no. 4, pp. 1311–1322, Dec. 2019, doi: 10.1007/s00202-019-00869-8.
- [54] P. Monica, M. Kowsalya, and J. M. Guerrero, "Logarithmic droop-based decentralized control of parallel converters for accurate current sharing in islanded DC microgrid applications," *IET Renewable Power Generation*, vol. 15, no. 6, pp. 1240–1254, Apr. 2021, doi: 10.1049/rpg2.12103.
- [55] S. Peyghami, H. Mokhtari, and F. Blaabjerg, "Decentralized Load Sharing in a Low-Voltage Direct Current Microgrid with an Adaptive Droop Approach Based on a Superimposed Frequency," *IEEE J Emerg Sel Top Power Electron*, vol. 5, no. 3, pp. 1205–1215, Sep. 2017, doi: 10.1109/JESTPE.2017.2674300.
- [56] M. Jafari, S. Peyghami, H. Mokhtari, and F. Blaabjerg, "Enhanced Frequency Droop Method for Decentralized Power Sharing Control in dc Microgrids," *IEEE J Emerg Sel Top Power Electron*, vol. 9, no. 2, pp. 1290–1301, Apr. 2021, doi: 10.1109/JESTPE.2020.2969144.
- [57] Y. Gu, X. Xiang, W. Li, and X. He, "Mode-adaptive decentralized control for renewable DC microgrid with enhanced reliability and flexibility," *IEEE Trans Power Electron*, vol. 29, no. 9, pp. 5072–5080, 2014, doi: 10.1109/TPEL.2013.2294204