International Journal of Engineering Trends and Technology
ISSN: 2231–5381 / https://doi.org/10.14445/22315381/IJETT-V72I8P132

Volume 72 Issue 8, 342-352, August 2024

Original Article

An Approach to Minimize Circulating Current and Load Sharing Error in Low Voltage DC Microgrid Through Adaptive Droop Control Technique

Shilpa Patel[1], Rajnikant Bhesdadiya[2], Hitesh Karkar[3]

[1]*Gujarat Technological University, Ahmedabad, Gujarat, India.*
[2]*Department of Electrical Engineering, L. E. College, Morbi, Gujarat, India.*
[3] *Department of Electrical Engineering, Government Engineering College, Rajkot, Gujarat, India.*

[1]*Corresponding Author : shilpa5185@gmail.com*

Received: 16 April 2024 Revised: 12 July 2024 Accepted: 31 July 2024 Published: 28 August 2024

Abstract **-** *Recently, Researchers have become increasingly interested in DC microgrids as a more efficient solution for local energy needs. These microgrids integrate modern electrical load, energy storage technology, and distributed generators. However, due to cable resistance, managing voltage at common DC bus and load current control becomes complex among power converters and DC gird terminals. This can lead to undesirable load sharing and increased circulating current. This research presents an adaptive droop control method that enhances load distribution among power converters and decreases circulating current with excellent voltage regulation. An Adaptive Droop Resistance (ADR) is calculated from the minimum difference between the converter's current and voltage deviations. A MATLAB code is implemented to select the adaptive droop resistance from a range of droop values. This resistance is then multiplied by the converter's current to produce a new reference for PI controllers. The adaptive droop control technique is simple and effective, requiring only bus voltage, converter voltages, and converter current to determine the new droop value. The research compares fixed lower droop, fixed higher droop, and the proposed adaptive droop control technique, providing a detailed explanation of load-sharing issues. With Conviction to this, a suggestion for future research is also provided. The feasibility of this suggested approach is simulated and analyzed using MATLAB/Simulink.*

Keywords *- DC microgrid, Load sharing, Voltage deviation, Droop control, Parallel converters.*

1. Introduction

The microgrid concept is broadly recognized for its ability to provide power to remote locations. The integration of microgrids is gaining significant interest in developing countries like India [1]. It is a commonly employed small-scale electrical grid that combines distributed generations, storage units, and loads. [2]. The primary categories of microgrids include DC (Direct Current), AC (Alternating Current), and hybrid microgrids. Integrating DC microgrids offers a range of benefits compared to AC microgrid integration. [3]. Although, it also has several disadvantages [4]. The primary constraints in a DC microgrid are load sharing and voltage management [5]. Usually, parallel converter topologies are used to distribute the load across multiple converters. Figure 1 illustrates the traditional architecture of a DC microgrid featuring parallel connected converters and loads. The parallel topology of converters enhances the system's reliability and flexibility [6]. Simultaneously, it also creates a problem of load sharing with minor changes in the converter's output voltage [7]. If it is not executed properly, it can lead to circulating current amongst the power converters. The common consequence of circulating current is that it can overload one converter while causing another converter to be underloaded. Additionally, it results in increased losses, heat generation, higher cost, and increased size of the converter [8]. Thus, reducing the circulating current and load-sharing error is crucial to implementing efficient control techniques. The other side of the coin also shows that it is important to maintain voltage regulation within the set limits while achieving the desired load sharing [9]. Various control techniques are suggested in the cited literature to minimize the load-sharing error. The common practice is to use active and passive load-sharing methods. There are various methods available for active load sharing [10]. Active load-sharing methods provide precise load-sharing and voltage regulation. Nevertheless, certain challenges must be tackled, including the requirement for high-bandwidth communication links and extra controllers, complex control strategy, potentially high costs, and limited flexibility [11].

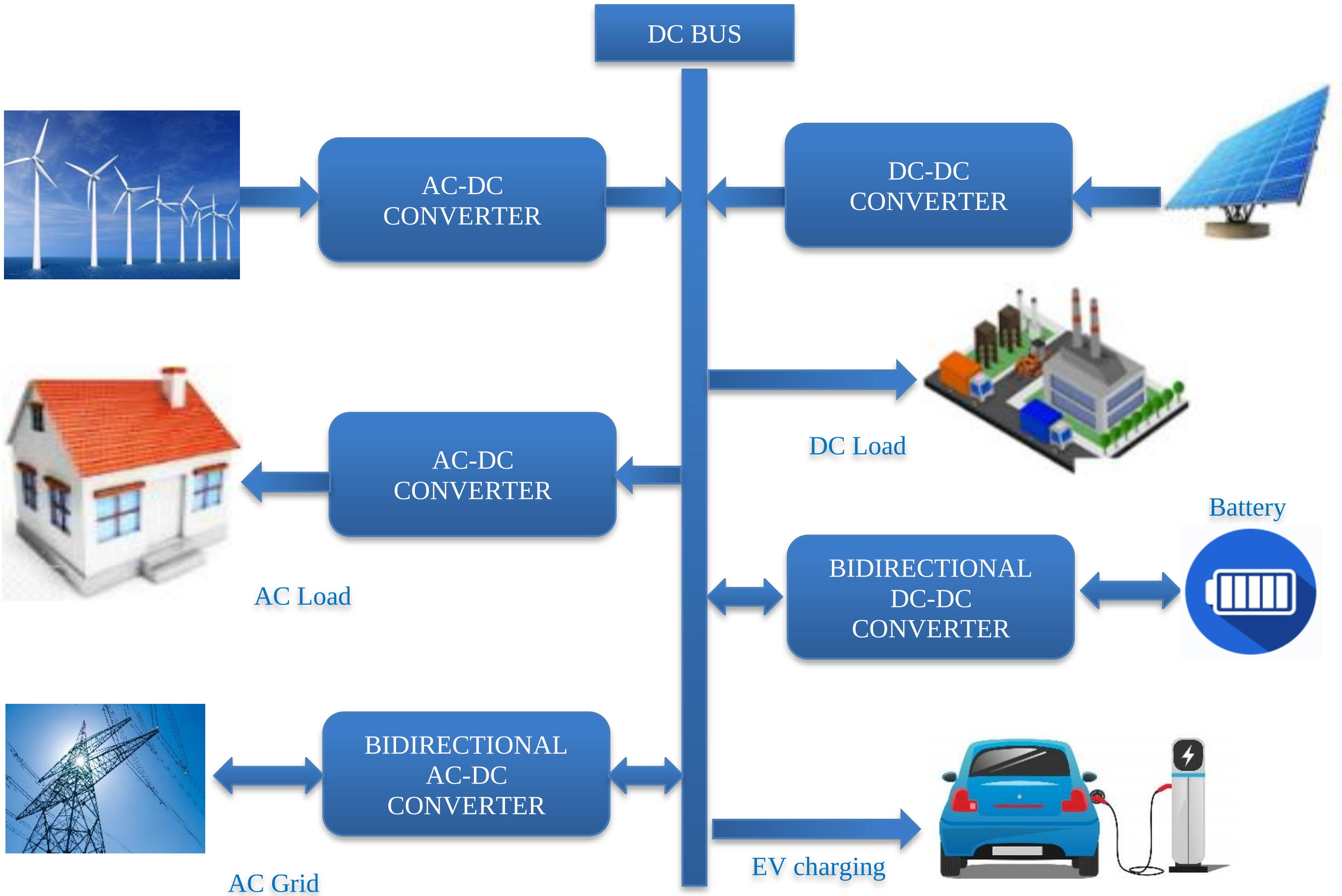

Fig. 1 The traditional architecture of a DC microgrid

On the other hand, the passive load-sharing method, commonly known as droop control, offers a seamless advantage compared to the active load-sharing methods [12]. Load distribution amongst many power resources is a notable advantage of droop control. It can be accomplished without the requirement of dedicated communication links. Therefore, it allows a decentralized and flexible control system. Usually, a method to achieve droop control involves adding "virtual resistance" into the current system. The "virtual resistance" remains constant regardless of operating conditions such as temperature and does not result in power loss [13]. Droop control is a decentralized approach that shares load equally across parallel converters in a DC microgrid, requiring only local measurements for voltage and current control[14]. Traditional droop control has a significant disadvantage as it cannot simultaneously share a proportional load while maintaining tight voltage regulation [15]. The existence of cable resistance further amplifies the possibility of circulating current and uneven distribution of load. Under such circumstances, the traditional droop control mechanism fails to achieve uniform distribution of the load current. Consequently, numerous decentralized droop control techniques have been proposed in scientific literature to tackle this limitation. The study presented by [16]shows that polynomial expression is a general representation that combines droop equations and minimizes the influence of sensors and cables. It also shows the enhanced performance under heavy load using a high-order polynomial. Nevertheless, the issue of achieving an optimal equilibrium between load distribution and voltage regulation remains unresolved, and the matter of circulating current is not tackled when using nonlinear droop control. The inverse droop control in [17] aims to achieve equal load sharing in series input and parallel output power converters with improved output voltage. However, the positive feedback input causes the system to be unstable. In [18], the piecewise linear formation of the droop curve is investigated to enhance current distribution and decrease the voltage deviation. A piecewise droop control sets a new value of droop resistance when the load current reaches a certain level. It provides an extensive solution for unstable performance at various load levels. However, the piecewise droop curve causes power converters to switch abruptly, which can lead to undesired transients and oscillations. Despite its potential improvements, its design process becomes complicated. In [19], A novel droop control method is aimed to enhance load-sharing accuracy.

It uses a secondary controller for data sharing. The data-sharing process employs low-bandwidth communication links, which may result in time delays and data loss. The study in [20] presents a new droop controller to minimize voltage deviation, ensuring even distribution of load current in the microgrid network and suppressing circulating current. Autonomous droop control is proposed in [21]. In [22], the cited work enhances the conventional droop control technique by dynamically determining the droop coefficients via an online selection process. This online adaption is a straightforward solution that minimizes fluctuations in bus voltage and enhances load sharing. This method regulates load sharing with a local controller but needs a secondary controller for voltage regulation. In [23], dispatchable droop control is suggested to address the issue of low voltage under high load conditions. The system automatically adjusts the droop factor to ensure constant voltage when there are changes in the load. In this method, transient occurrence can be observed when the load changes, which is undesirable. The article presented in [24] is a design method for determining the nonlinear droop slope constant at a given heavy load range. In addition, an upward (negative droop) slop has been employed to improve voltage regulation at light load conditions. An advanced adjustable droop control technique utilizing computational calculations is demonstrated in [25]. It rapidly computes the value of the droop constant in response to variations in the source voltage, ensuring proper load sharing between converters. This mitigates the occurrence of circulating current phenomena while enhancing voltage regulation. The model is constrained to only two parallel converters and experiences peak overshoot and disturbances.

The approaches mentioned earlier include certain significant drawbacks. These include the necessity of extra secondary controllers, a requirement of communication links, voltage regulation issues, complex calculations, system complexity due to using a secondary controller, transients, instability, and the occurrence of circulating current problems. The proposed work presents an adaptive droop control technique as a potential solution to mitigate the aforementioned limitations. A method has been developed to minimize load-sharing error and circulating current while maintaining excellent voltage regulation with a simple and effective load-sharing strategy. An Adaptive Droop Control (ADR) technique works based on the different index values of the droop constant. The index values of the droop constant start from the minimum droop value to the maximum possible droop value that tightens the permissible voltage regulation. The function of ADR is to choose the smallest droop resistance value when the difference between current deviation and voltage deviation is minimum. In this manner, the smallest droop value can be achieved, ensuring proportional load sharing and reducing circulating current with excellent voltage regulation. The subsequent section delineates the issues associated with load sharing and circulating current.

1.1. Issues Related to Load Sharing and Circulating Currents

Here, the parallel operation of two buck converters with common loads is explained in Figure 2(a). The challenges associated with this setup are depicted in Figure 2(b). V_{in1} and V_{in2} output voltages from different renewable sources, while V_{o1} and V_{o2} are the converter's output voltages. I_{o1} and I_{o2} indicate the converter's output currents, and I_o is the load current. R_{c1} and R_{c2} are the cables' resistances for converters 1 and 2, respectively. Lastly, V_{dc} is the DC bus voltage. Figure 2 depicts a schematic diagram of two converters with the same load (a) and their equivalent circuit (b). When V_{o1} is greater than V_{o2}, a circulating current, known as Icir, will be initiated, flowing from the first converter to the second converter. Consequently, this will lead to the excessive burdening of one converter and insufficient burdening of another converter.

By utilizing Kirchoff's law in Figure 2(b)

$$V_{o1} - I_{o1}\, R_{c1} - I_o\, R_L = 0 \tag{1}$$

$$V_{o2} - I_{o2}\, R_{c2} - I_o\, R_L = 0 \tag{2}$$

By applying equations (1) and (2), it is possible to determine the converter's output currents Io1 and Io2. These equations are as follows:

$$I_{o1} = \frac{V_{o1}\,(R_{c2} + R_L) - V_{o2}\, R_L}{R_{c1}\, R_{c2} + R_L\, R_{c1} + R_L\, R_{c2}} \tag{3}$$

$$I_{o2} = \frac{V_{o2}\,(R_{c1} + R_L) - V_{o1}\, R_L}{R_{c1}\, R_{c2} + R_L\, R_{c1} + R_L\, R_{c2}} \tag{4}$$

In addition, the circulating current is derived as:

$$I_{c12} = -I_{c21} = \frac{V_{o1} - V_{o2}}{R_{c1} + R_{c2}} = \frac{I_{o1}\, R_{c1} - I_{o2}\, R_{c2}}{R_{c1} + R_{c2}} \tag{5}$$

Based on equation (5), it becomes obvious that the presence of uneven cable resistance leads to the initiation of circulating current between converter-1 and converter-2. Therefore, converters are required to provide both load current and circulating current.

$$I_{o1} = \frac{R_{c2}\, V_{o1}}{R_{c1}\, R_{c2} + R_{c1}\, R_L + R_{c2}\, R_L} + \frac{V_{o1} - V_{o2}}{R_{c1} + R_{c2}} \tag{6}$$

$$I_{o2} = \frac{R_{c1}\, V_{o2}}{R_{c1}\, R_{c2} + R_{c1}\, R_L + R_{c2}\, R_L} + \frac{V_{o2} - V_{o1}}{R_{c1} + R_{c2}} \tag{7}$$

Equations (5), (6), and (7) indicate that the circulating current is the crucial parameter while connecting several converters in parallel. As previously stated, droop resistance is vital in achieving uniform load sharing across all converters.

Figure 3 illustrates an equivalent circuit of parallel connected converters with droop resistance and cable resistance. The reduction in voltage caused by the addition of droop control and cable resistance can be mathematically represented by:

$$V_{dc} = V_{oi} - R_{ci}\, I_{oi} - R_{di}\, I_{oi} \tag{8}$$

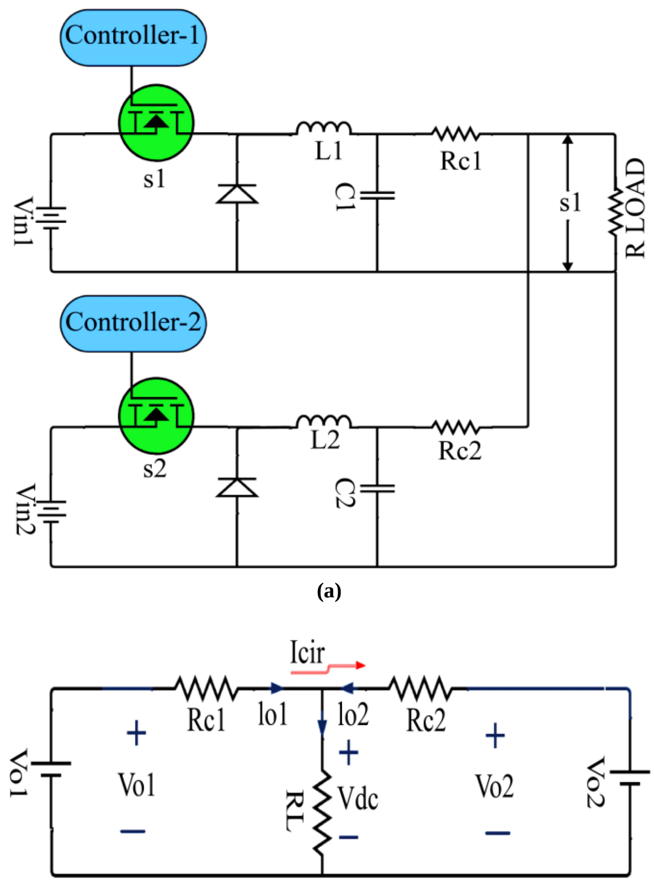

Fig. 2 Schematic diagram of two converters with the same load (a) and its equivalent (b)

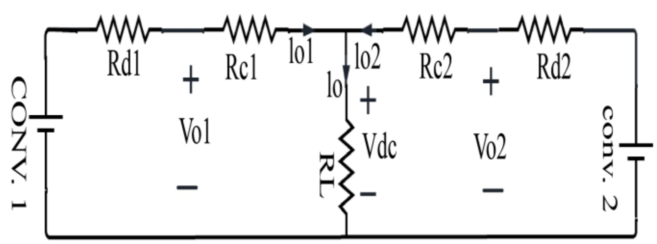

Fig. 3 An equivalent circuit of parallel connected converters with droop resistance and cable resistance

Where the parameter V_{oi} represents the voltage at the output terminals of the i^{th} converter. Now, the bus voltage will be:

$$V_{dc} = (V_{ref} - R_{d1}I_{o1}) - R_{c1}I_{o1} \tag{9}$$

$$V_{dc} = (V_{ref} - R_{d2}I_{o2}) - R_{c2}I_{o2} \tag{10}$$

According to the provided equations, the droop resistance and cable resistance are connected in series, leading to an extra voltage decrease along the line. By combining (9) and (10), the ratio of output currents is as follows:

$$\frac{I_{o1}}{I_{o2}} = \frac{R_{c2} + R_{d2}}{R_{c1} + R_{d1}} \tag{11}$$

According to the theory mentioned above, it is important to have proper current sharing in microgrid operations. This helps to prevent converters from circulating currents and overloading, which is highly desirable. In practical situations where cable resistances are significant, the traditional droop control is inadequate to guarantee proportional current distribution among the power sources. It happens because the voltage drops across the cable resistances are uneven.

2. Method

An adaptive droop control technique has been introduced in this section that aims to minimize load-sharing error and circulating current while achieving excellent voltage regulation. Figure 4 represents the adaptive droop control technique with a block diagram arrangement. In this research, the droop value is chosen in ascending order, starting from the lowest value and ending with the highest value.

The adaptive droop resistance can be chosen from a variety of indexed values. The following mathematical calculations are provided to determine the adaptive droop resistance (ADR):

$$\text{ADR} = |\min[\tfrac{1}{4}\{I_{devj} - V_{devj})]| \tag{12}$$

The difference between the rated current of converters and the actual current of the j^{th} converter is represented by I_{devj}. Similarly, V_{devj} represents the deviation in the output voltage of the j^{th} converter in relation to the reference voltage. The value of I_{devj} and V_{devj} can be calculated as:

$$I_{devj} = I_{rated} - I_{oj} \tag{13}$$

$$V_{devj} = V_{ref} - V_{oj} \tag{14}$$

Estimation of the minimum value of ADR can be achieved by inputting the values of (13) and (14) in equation (12). Figure 5 illustrates the relationship between droop resistance, voltage deviation, and current difference. It is worth mentioning that the droop resistance is restricted by the maximum voltage deviation at the point of common coupling. In the adaptive droop control method, the droop resistance is determined to minimize both voltage deviation and current deviation.

The equations provided below can be used to determine the values of output currents.

$$I_{o1} = \frac{V_{o1}\,(R_{c2} + R_{d2} + RL) - RL\,V_{o2}}{k} \tag{15}$$

$$I_{o2} = \frac{V_{o2}\,(R_{c2} + R_{d2} + RL) - RL\,V_{o1}}{k} \tag{16}$$

Here,

$$k = \big((R_{c2} + R_{d2})\,(R_{c2} + R_{d2})\big) + \big(RL(R_{c2} + R_{d2})\big) + \big(RL(R_{c2} + R_{d2})\big)$$

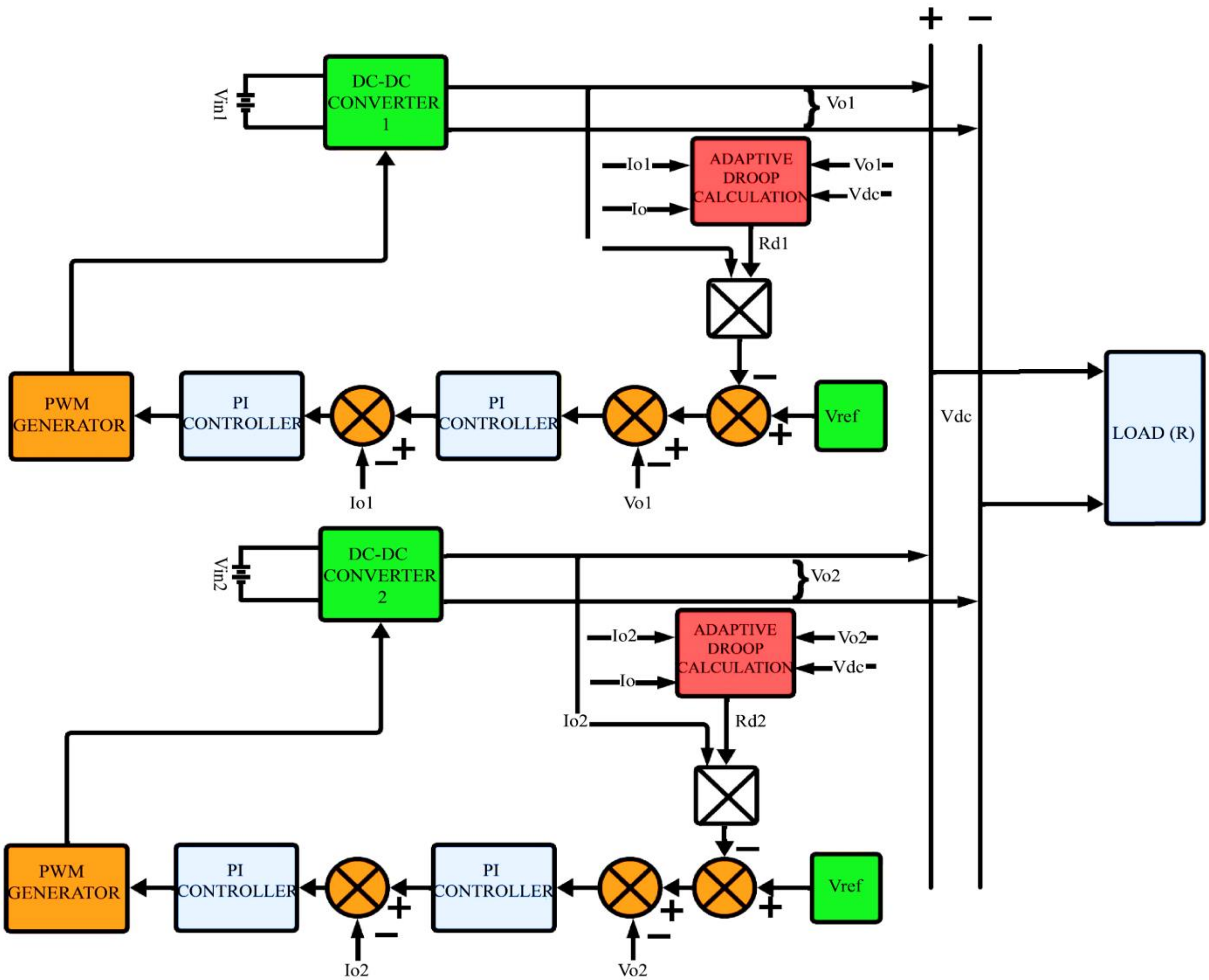

Fig. 4 Representation of the proposed adaptive droop control technique

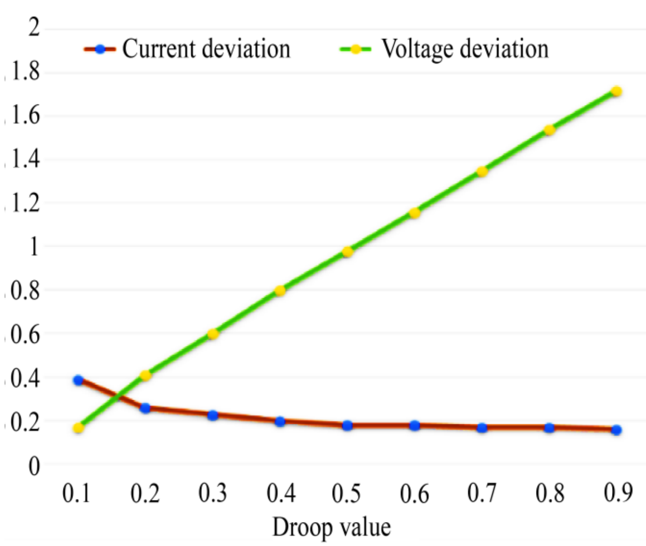

Fig. 5 Current and voltage deviation versus droop value

Similarly, the output voltage of each converter is determined by:

$$V_{o1} = (R_{d1} + R_{c1})\, I_{o1} + RL\, I_o \tag{17}$$

$$V_{o2} = (R_{d2} + R_{c2})\, I_{o2} + RL\, I_o \tag{18}$$

Through the combination of equations (13) to (18) and their substitution into equation (12), the smallest value of ADR is attained. The droop constant associated with the smallest ADR represents the suitable droop resistance for the adaptive droop control technique.

The power loss produced by droop resistance and cable resistance can be given by equation (19) and (20). Total power loss is the sum of power loss produced by both converters.

$$P_{loss1} = {I_{o1}}^2 * (R_{d1} + R_{c1}) \tag{19}$$

$$P_{loss2} = {I_{o2}}^2 * (R_{d2} + R_{c2}) \tag{20}$$

$$P_{loss} = P_{loss1} + P_{loss2} \quad (21)$$

The adaptive droop control technique just necessitates the output voltage of converters, bus voltage, and load current for the droop calculation. Once the droop value is calculated, it is subsequently multiplied by the output current of the converter to produce an updated voltage reference for the PI controller. The control mechanism utilizes two Proportional-Integral (PI) controllers to regulate the current and voltage of the converter. Then, the PI controller's output is subsequently transmitted to the PWM generator, which generates the required pulse output for the power converters.

Figure 6 demonstrates a Flowchart illustrating the implementation of an adaptive droop control technique. The control approach specifies the range of droop resistance values for the MATLAB function. The specified voltage regulation limits the maximum value of droop resistance.

In this case, the allowable voltage deviation is 4%. Different cable resistances are provided to MATLAB to observe its effect on voltage regulation, load sharing, and circulating current. Instantaneous droop resistance calculations and power loss. MATLAB analyses the above-related equations and calculates the lowest possible value of droop resistance using equation (12).

3. Results and Discussion

Using a parallel configuration, two DC-DC buck converters are designed and simulated in MATLAB/Simulink. System specifications for the two converters are as per Table 1. The simulation examines load sharing, voltage regulation, circulating current, instantaneous droop resistance calculations, and power loss produced by cable and adaptive droop resistances.

The analysis uses three different methods. These methods are fixed lower droop control, fixed higher droop control, and adaptive droop control. Table 1 shows the specifications of a given system.The two converters are designed for the same rating. The input voltage and current are also taken similarly for both converters. The values of the inductor and capacitors are calculated carefully to get the desired output without disturbance.

Case one demonstrates the simulation of fixed lower droop control. Case two demonstrates the implementation of a fixed higher droop method, while case three showcases an adaptive droop control method. The simulations comprehensively analyze various parameters, including bus voltage, converter current, converter voltage, and circulating current. The load resistance undergoes two changes during the specified time intervals. Initially, it is set at 48Ω from 0 to 0.5 second, then adjusted to 12.3Ω from 0.5 to 1 second. The cable resistances for converter-1 and converter-2 are taken to be 0.1Ω and 0.2Ω, respectively.

Table 1. Specifications of a given system

Specifications	Rated value
Rated converter power	96W
Rated converter voltage	48V
Rated converter current	2A
Inductor value	750µH
Capacitor value	2220µF
Frequency of switching	5KHz
ESR of inductor	0.68Ω
ESR of capacitor	0.18Ω

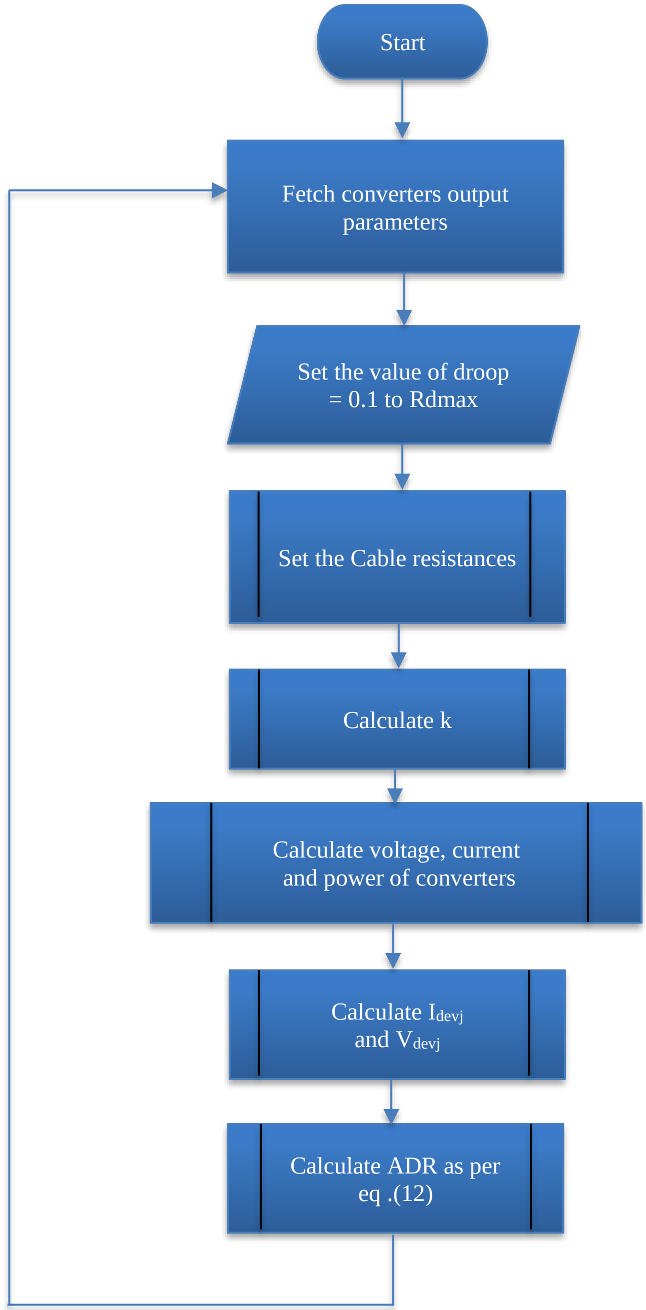

Fig. 6 Flowchart illustrating the implementation of an adaptive droop control technique

3.1. Case 1-Fixed Lower Droop Control

Figure 7 represents the simulation of two buck converters with a traditional fixed lower droop control. The traditional lower droop control employs a specific constant droop resistance. The traditional fixed droop value does not require a dedicated calculation.

Thus, the control is simple and robust. Based on the data presented in Figure 7 (a, b, c, and d), it is observed that the deviation in voltage is minimal, with a voltage regulation of 0.31%.

Additionally, the load-sharing error is 14% when the load current is 1A. As the load increases from 48Ω to 12.3Ω, the issue of load sharing becomes more significant. The load sharing error reaches a value of 15.38%, with a circulating current of 0.6A flowing from converter one to another.

The voltage regulation was measured at 1.25%, and the power delivered to the load was 181.6W. Therefore, it is possible to achieve effective voltage regulation using fixed lower droop control; however, this approach results in poor load sharing. Additionally, the circulating current increases as the load current increases.

3.2. Case 2-Fixed Higher Droop Control

Figure 8 shows the simulation with a traditional fixed higher droop control. From the data shown in Figure 8 (a, b, c, and d), it is observed that there is a voltage regulation of 1.39% with 48Ω load resistance. As the load increases from 48Ω to 12.3Ω, the voltage regulation deteriorates significantly. The measured voltage regulation is 5.25%, and the load sharing error is 5%, with a load current of 1A. Currently, the circulating current is at its lowest level. As the load increases from 48Ω to 12.3Ω, the load-sharing error is only 3.5%, with a circulating current of 0.14A.

So, the higher droop setting results in equal load sharing, yet at the charge of voltage regulation. Due to voltage drop, the load current and load power is also reduced. At this time, the load current is 3.67A. Based on the analysis of the above cases, it is evident that implementing the fix-lower droop method has a detrimental effect on the load-sharing accuracy of power converters. The circulating current reaches its peak in the lower droop control method. However, it does offer excellent voltage regulation. By implementing higher droop control, load-sharing accuracy can be improved at the cost of voltage regulation. The increased droop resistance adversely affects the bus voltage.

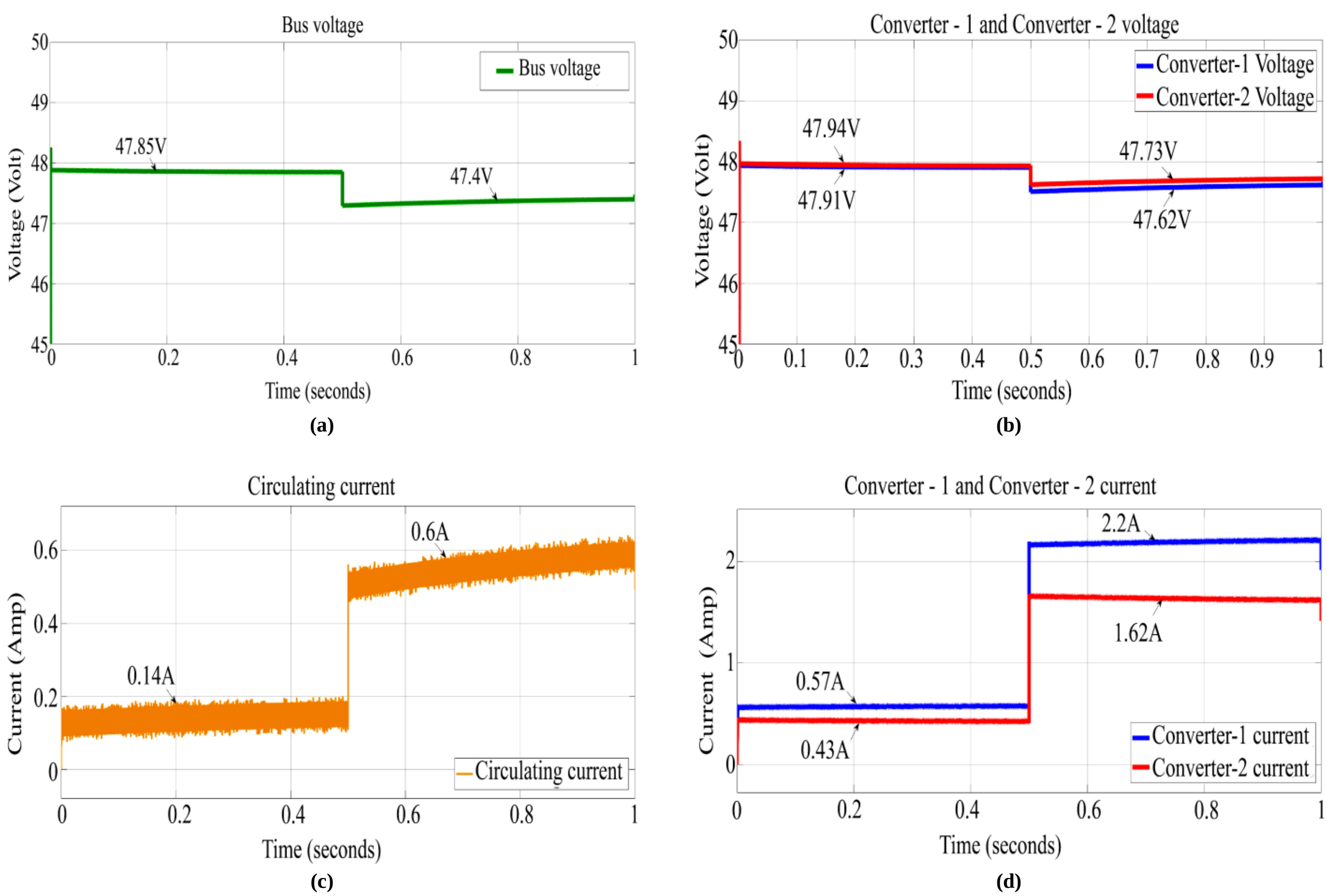

Fig. 7 Traditional fixed lower droop control: (a) DC bus voltage, (b) Output voltage of converter1 and converter-2, (c) Circulating current, (d) Output current of converter-1 and converter-2

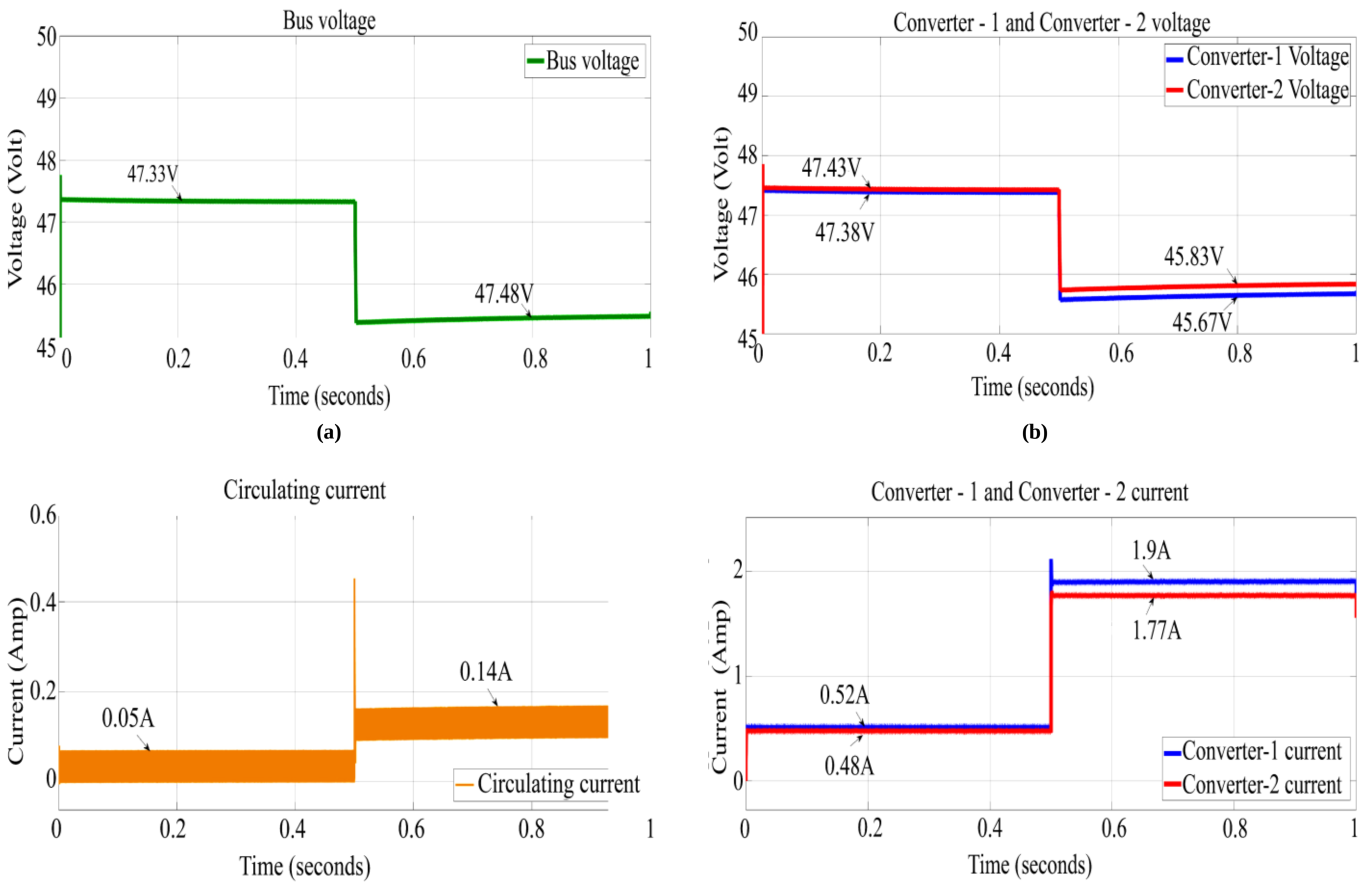

Fig. 8 Traditional fixed higher droop control: (a) DC bus voltage, (b) Output voltage of converter1 and converter-2, (c) Circulating current, (d) Output current of converter-1 and converter-2

3.3. Case 3-Adaptive Droop Control Approach

Figure 9 illustrates the results obtained by implementing an adaptive droop control technique. Based on the information provided in Figure 9 (a, b, c, and d), the voltage regulation is 0.54% and 0.83% when the load resistance varies from 48Ω to 12.3Ω, respectively. Therefore, excellent voltage regulation is attained. The bus voltage remains constant, fluctuating slightly between 47.74V and 47.6V. The power delivered to the load is also highest. As per Figure 9 (a, b, c, and d), load-sharing error is minimal at light load, which tightens the voltage regulation. With an increase in the load current to 3.9 A, the load sharing becomes 1.81%. Therefore, optimal load distribution is achieved.

The circulating current is approximately 0.07A, which demonstrates the efficiency of the proposed adaptive droop technique. It is worth noting that when the current sharing error is minimized, the load current and load power experience a boost. According to the findings of an adaptive droop control method, it has been demonstrated that voltage regulation and proportional load sharing are effectively attained with minimal load sharing error. This is accomplished by adjusting the droop value from the minimum to the maximum droop resistance and choosing the minimum Value of ADR.

The rigorous settings of the PI controller negatively impact the converter's current waveforms during load fluctuations. Nevertheless, the PI controller effectively nullifies the error within a mere 0.8 seconds, leading to a steady output. Table 2 illustrates the comparison of all three methods that have been simulated and analyzed in the present research article.

Figure 10(a) represents the instantaneous value of the adaptive droop resistance for converter-1 and converter-2. At a load resistance of 48Ω, the ADR1 value is 0.39. When the load resistance is increased from 48Ω to 12.3Ω, the ADR1 value decreases to 0.16. Similarly, the AD2 value decreases from 0.37 to 0.07 as the load is increased from 48Ω to 12.3Ω.

Thus, it has been demonstrated that both controllers function autonomously. The droop value is adjusted to regulate the bus voltage effectively while minimizing load-sharing error.

Consequently, the circulating current is also minimized. Figure 10(b) illustrates the power loss resulting from the resistance of the cable and the droop resistance. The power loss generated by both resistances is insignificant.

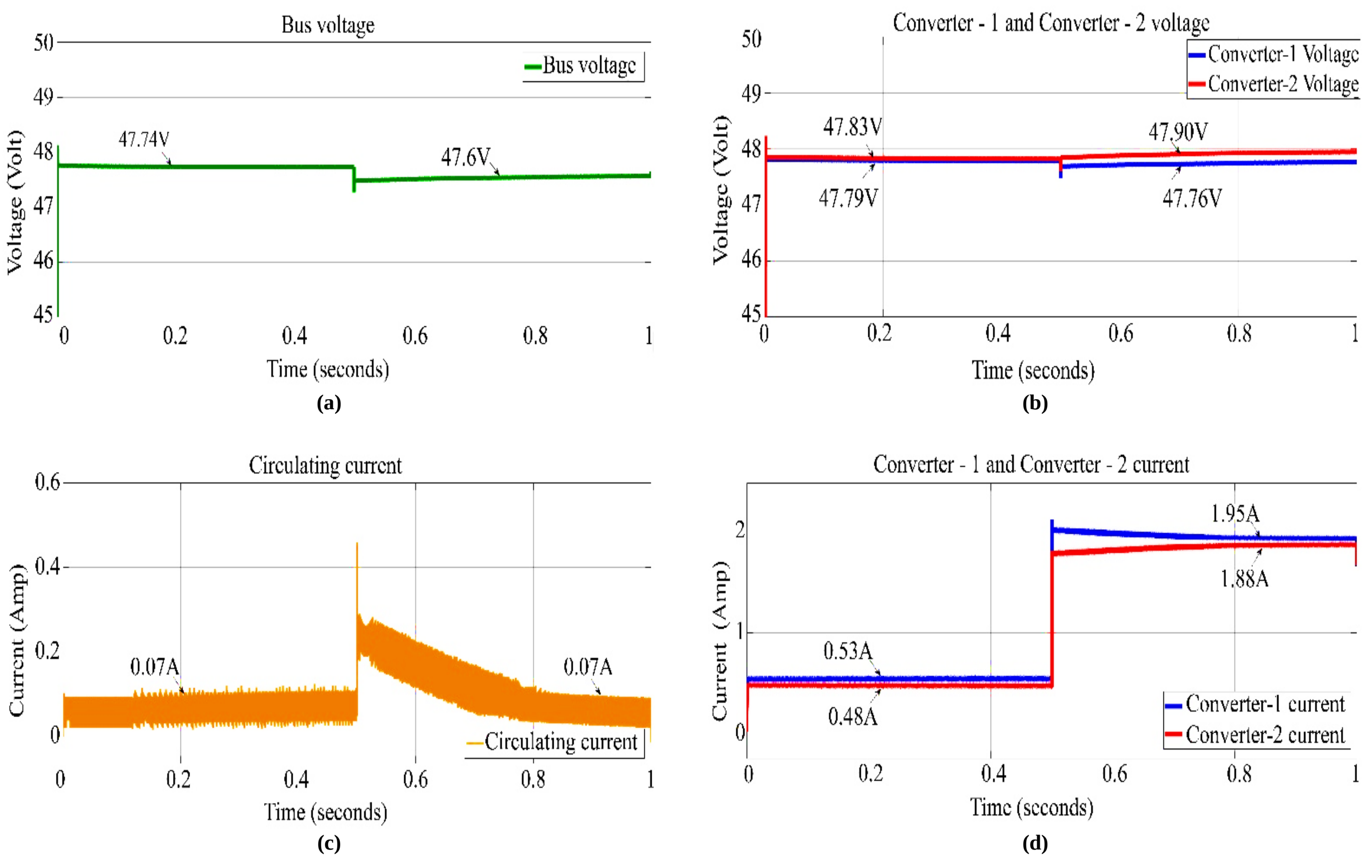

Fig. 9 An Adaptive droop control technique : (a) DC bus voltage, (b) Output voltage of converter1 and converter-2, (c) Circulating current, (d) Output current of converter-1 and converter-2

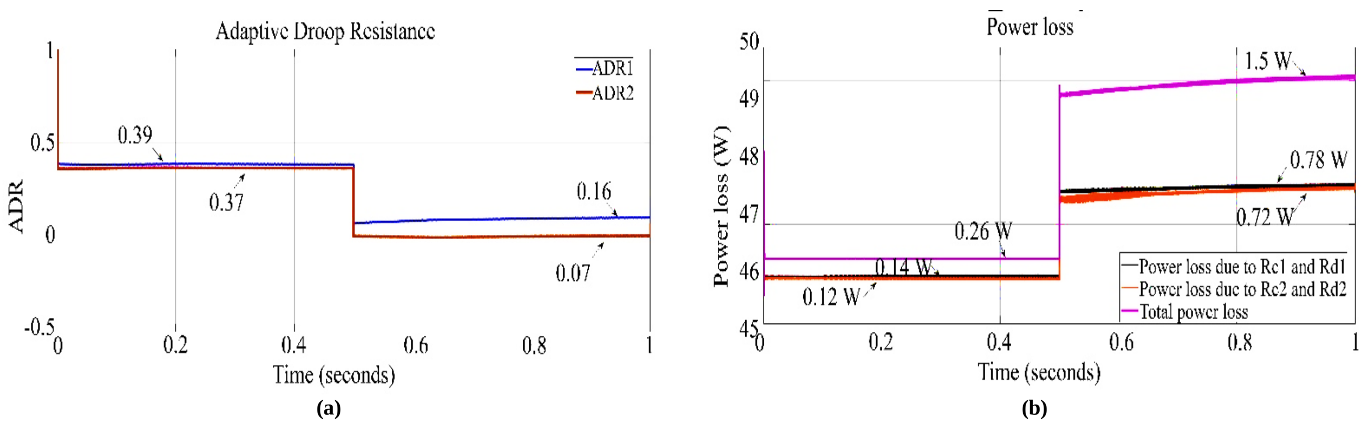

Fig. 10 An Adaptive droop control technique : (a) Instantaneous adaptive droop resistances (ADR) for converter-1 and converter-2, (b) Converter's output power loss and total power loss due to cable resistance and adaptive droop resistance

The converters operate at a low power level, with converter-1 consuming 0.14W and converter-2 consuming 0.12W. The cumulative power dissipation amounts to a mere 0.26 watts within the time interval from 0 to 0.5 seconds. After 0.5 seconds, there was a proportional increase in power loss as the load increased. During the time interval of 0.5 to 1.0 seconds, the converters reach their maximum capacity and experience a power loss of only 1.5W. This demonstrates that the power loss is minimal even under different load conditions compared to traditional droop control.

After carefully examining Table 2, it becomes apparent that there is consistently a compromise between load sharing and voltage regulation when employing conventional droop control methods, whether set to higher or lower values. The findings from traditional droop control methods also serve as a useful reference for future researchers. This research paper presents a unique approach to address the issue of load-sharing error and circulating current while simultaneously achieving excellent voltage regulation. This method presents a promising solution for the future DC microgrid.

Table 2. Comparison of different methods at full load

Parameters	Fixed lower droop method	Fixed higher droop method	Adaptive droop control technique (ADR)
Load Sharing Error	15.38%	3.5%	1.81%
Circulating current	0.6A	0.14A	0.07A
Voltage regulation	1.25%	5.25%	0.83%
Bus voltage	47.4V	45.48V	47.6V
Droop resistance	Fixed	fixed	Instantaneous adaptive
Power loss	1.75W	9.1W	1.5W

4. Conclusion

This research work presents an adaptive droop control technique that aims to minimize circulating current and load-sharing error in low-voltage DC microgrids. An adaptive droop control technique rapidly determines the droop resistance by considering an array of indexed droop values. The simulation results clearly demonstrate the efficacy of the proposed technique in managing fluctuating loading conditions. This study examines the analysis of three methods: the fixed lower droop method, the fixed higher droop method, and the proposed adaptive droop control method. The comparison highlights the advantages of using an adaptive droop control technique that enhances load-sharing capabilities and efficiently reduces circulating current while maintaining excellent voltage regulation. The adaptive droop control technique reduces load sharing error to 1.81%, which is 15.38% in the case of the fixed lower droop control method. The simulation results show that the voltage regulation has been enhanced by 0.83%, which is 5.25% in the case of fixed higher droop control.

The circulating current decreased to 0.07A, which is 0.6A, in the case of the fixed droop control method. The power loss in the proposed method is only 1.5W at full load, which is significantly lower than the power loss in fixed higher droop control. Therefore, the results obtained by the adaptive droop control technique guarantee excellent performance under any load condition. Theoretical values and simulation results are found to be identical. Future investigations will be conducted to evaluate the efficacy of an adaptive droop control technique compared to various alternative load-sharing methods.

Acknowledgements

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

References

[1] Sheetal Chandak, and Pravat K. Rout, “The Implementation Framework of a Microgrid: A Review,” *International Journal of Energy Research*, vol. 45, no. 3, pp. 3523-3547, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[2] Moslem Uddin et al., “Microgrids: A Review, Outstanding Issues, and Future Trends,” *Energy Strategy Reviews*, vol. 49, pp. 1-16, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[3] Vitor Fernão Pires, Armando Pires, and Armando Cordeiro, “DC Microgrids: Benefits, Architectures, Perspectives, and Challenges,” *Energies*, vol. 16, no. 3, pp. 1-20, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[4] Rafat Aljarrah et al., “Issues and Challenges of Grid-Following Converters Interfacing Renewable Energy Sources in Low Inertia Systems: A Review,” *IEEE Access*, vol. 12, pp. 5534-5561, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[5] Muhammad Rashad, and Uzair Raoof, “Equivalent SM Controller for Load-Sharing and Dynamic Performance in a DC Microgrid Application,” *Mathematical Problems in Engineering*, vol. 2022, no. 1, pp. 1-17, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[6] Aphrodis Nduwamungu et al., “Control Strategies and Stabilization Techniques for DC/DC Converters Application in DC MGs: Challenges, Opportunities, and Prospects—A Review,” *Energies*, vol. 17, no. 3, pp. 1-28, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[7] Alaa Mohd et al., “Review of Control Techniques for Inverters Parallel Operation,” *Electric Power Systems Research*, vol. 80, no. 12, pp. 1477-1487, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[8] Niloofar Ghanbari, and Subhashish Bhattacharya, “Adaptive Droop Control Method for Suppressing Circulating Currents in DC Microgrids,” *IEEE Open Access Journal of Power and Energy*, vol. 7, pp. 100-110, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[9] Liyuan Gao et al., “A DC Microgrid Coordinated Control Strategy Based on Integrator Current-Sharing,” *Energies*, vol. 10, no. 8, pp. 1-17, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[10] Tsai-Fu Wu, Yu-Kai Chen, and Yong-Heh Huang, “3C Strategy for Inverters in Parallel Operation Achieving an Equal Current Distribution,” *IEEE Transactions on Industrial Electronics*, vol. 47, no. 2, pp. 273-281, 2000. [CrossRef] [Google Scholar] [Publisher Link]

[11] P. Monica, M. Kowsalya, and Josep 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, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[12] Qianwen Xu et al., "A Robust Droop-Based Autonomous Controller for Decentralized Power Sharing in DC Microgrid Considering Large-Signal Stability," *IEEE Transactions on Industrial Informatics*, vol. 16, no. 3, pp. 1483-1494, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[13] Fei Gao et al., "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. [CrossRef] [Google Scholar] [Publisher Link]

[14] Babangida Modu et al., "DC-based Microgrid: Topologies, Control Schemes, and Implementations," *Alexandria Engineering Journal*, vol. 70, pp. 61-92, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[15] Fei Gao et al., "Analysis of Droop Control Methods in DC Microgrid," *2014 16th European Conference on Power Electronics and Applications*, Lappeenranta, Finland, pp. 1-9, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[16] Fang Chen et al., "Investigation of Nonlinear Droop Control in DC Power Distribution Systems: Load Sharing, Voltage Regulation, Efficiency, and Stability," *IEEE Transactions on Power Electronics*, vol. 34, no. 10, pp. 9404-9421, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[17] Guo Xu, Deshang Sha, and Xiaozhong Liao, "Decentralized Inverse-Droop Control for Input-Series-Output-Parallel DC-DC Converters," *IEEE Transactions on Power Electronics*, vol. 30, no. 9, pp. 4621-4625, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[18] Pu Zhao, Zeng Liu, and Jinjun Liu, "An Adaptive Discrete Piecewise Droop Control in DC Microgrids," *IEEE Transactions on Smart Grid*, vol. 15, no. 2, pp. 1271-1288, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[19] Niloofar Ghanbari, and Subhashish Bhattacharya, "Suppressing Circulating Currents of Battery Management Systems in Droop-Based Microgrids," *2020 IEEE Transportation Electrification Conference & Expo (ITEC)*, Chicago, IL, USA, pp. 871-876, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[20] Pascal Hategekimana et al., "Improved Methods for Controlling Interconnected DC Microgrids in Rural Villages," *AIMS Energy*, vol. 12, no. 1, pp. 214-234, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[21] Huijuan Li et al., "Autonomous and Adaptive Voltage Control Using Multiple Distributed Energy Resources," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 718-730, 2013.[CrossRef] [Google Scholar] [Publisher Link]

[22] Mohamed A. Mesbah et al., "Adaptive Control Approach for Accurate Current Sharing and Voltage Regulation in DC Microgrid Applications," *Energies*, vol. 17, no. 2, pp. 1-19, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[23] Yantao Liu et al., "Dispatchable Droop Control Strategy for DC Microgrid," *Energy Reports*, vol. 9, pp. 98-102, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[24] Yaoyao Zhang et al., "Design of Nonlinear Droop Control in DC Microgrid for Desired Voltage Regulation and Current Sharing Accuracy," *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, vol. 11, no. 1, pp. 168-175, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[25] Prudhvi Kumar Gorijeevaram Reddy, Sattianadan Dasarathan, and Vijayakumar Krishnasamy, "Investigation of Adaptive Droop Control Applied to Low-Voltage DC Microgrid," *Energies*, vol. 14, no. 17, pp. 1-20, 2021. [CrossRef] [Google Scholar] [Publisher Link]