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Enhancing stability and voltage quality in remote DC microgrid systems through adaptive droop control approach

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ABSTRACT

To ensure the stable and accurate operation of "rural areas", a reliable power source is necessary, and voltage issues must be carefully considered in power system design to ensure patient safety. Remote DC microgrids provide a viable option for transferring energy across power sources while assuring stability and high efficiency. In this paper, an adaptive droop control approach is developed and compared to the standard droop control method. The suggested technique recommends a dynamic modification of droop coefficients intending to effectively limit the buildup of mistakes in current sharing and departures from the preset voltage setpoints. Through the implementation of the adaptive droop control method, the remote DC microgrid not only enhances current balancing performance but also contributes to a substantial improvement in voltage stability, thereby increasing the overall operational efficiency of the system. Simulation and experimental results on a small-scale remote DC microgrid validate the proposed adaptive droop control approach, proving its effectiveness in the small-scale microgrid system.

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1. INTRODUCTION

A remote DC microgrid is a localized energy system that can connect to the main grid and run independently. Even though remote DC microgrids normally operate while linked to the grid, they can seamlessly transition to their on-site generation in the case of a grid interruption [1]–[3]. The site or community it serves benefits from this ability to disconnect from the grid, which increases reliability and resilience. In developing countries, developed nations strategically invest in DC microgrid systems for remote areas, aiming to enhance energy access, promote sustainable development, and empower local communities. In particular, the Australian government has pioneered the development of microgrid systems on Lord Howe Island and Kangaroo Island, integrating advanced battery storage systems and photovoltaic panels to enhance energy resilience and sustainability in these remote regions [4].

Figure 1 displays the usual structure of a remote DC microgrid system. In Figure 1, the renewable energy sources, energy storage systems, and essential load devices are linked to a singular bus that creates a DC microgrid system. Remote DC microgrids is simple to integrate renewable energy sources, energy storage systems, and devices employing DC power. At the same time, microgrids can function independently for extensive periods and have the capacity to convert energy sources flexibly and reliably.

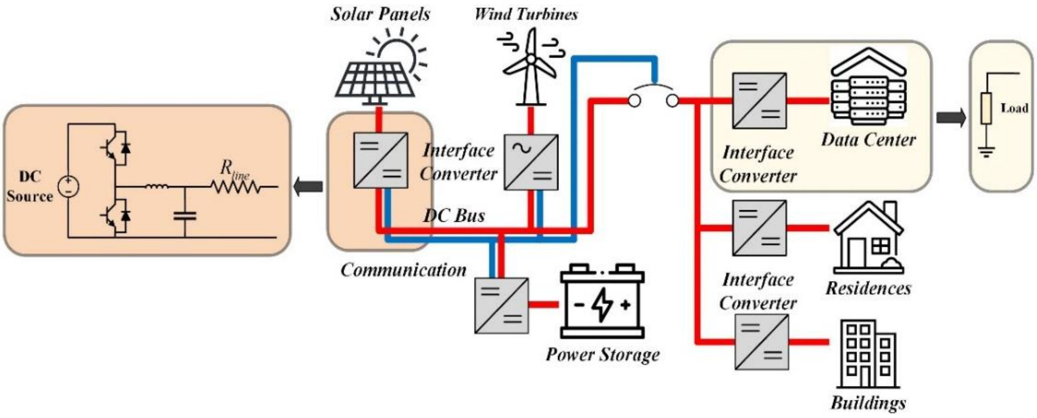


Figure 1. Remote DC microgrid structure

In the remote DC microgrids, droop control is one of the most often utilized methods for managing capacity and ensuring the stability of the power grid system [5]–[9]. This control approach adapts dynamically in response to variations in load and power, assisting in balancing output power and demand across the system [10], [11]. Furthermore, the system may have a secondary control element that, in conjunction with the communication and control system, manages the functioning of the system's components [12], [13]. In conclusion, the use of control mechanisms is critical for the stable and efficient functioning of DC microgrids.

However, this strategy has numerous downsides. This control approach is fundamentally control based on proportional characteristics, the output voltage or output current is calculated and modified depending on changes in power consumption on the system. Therefore, this technique has no mechanisms to avoid voltage fluctuations or dips on the system, resulting to imbalance and instability [14]. This difficulty can lead to adjustments in the system. unforeseen variations in the power supply, notably during unexpected changes in received or transmitted power on the system.

To overcome the disadvantage of the conventional control method, a control method using automatically adjusted droop parameters was introduced [15]–[17]. This technique has achieved success in minimizing errors in sharing, but in return, the voltage drop problem has not been solved. A decentralized circulating current control strategy based on no-load circulating current values is described in [18]–[20]; nevertheless, the fundamental issue with this algorithm is its no-load operation.

A study conducted in [21], [22], introduced a droop control method incorporating voltage shifting, aiming to reduce deviation in the bus voltage. This approach offers several benefits, including the independence of the output voltage of the converters from the magnitude of droop and its consideration of the impact of cable line resistance. Nonetheless, the proposed technique relies on a fixed droop gain resistance to enhance current sharing while also improving voltage regulation, resulting in high current sharing. On the other hand, the technique of using the piecewise characteristic has also been introduced [23]. This method uses a way of dividing the droop value into segments, which improves the efficiency of sharing compared to the conventional droop technique when only using linear droop lines. However, the reduced voltage quality is an inevitable disadvantage of this control method.

In this paper, we present a novel adaptive droop control strategy for boosting voltage regulation and load-sharing accuracy in a remote DC microgrid system. The suggested technique dynamically manages droop coefficients to reduce the buildup of mistakes in current sharing and divergence from the required voltage. The adaptive droop control strategy optimizes current balance while simultaneously raising voltage. Even when the input power changes quickly, the output currents of multi-generators efficiently monitor the balancing current value and maintain DC bus voltage quality. Simulations of the suggested approach were done using MATLAB/Simulink software, and its effectiveness was compared to that of the usual droop control method under different operating scenarios. Furthermore, actual results with small-scale remote DC microgrids are utilized to substantiate the feasibility of the suggested adaptive droop control technique.

This paper is organized into several sections: i) Section 2, which discusses the disadvantages of the conventional control method, section 2.1. delves into the circulating current analysis for the two-converter system, while section 2.2. explores load power sharing through the conventional droop control method; ii) Section 3 introduces the principle of the proposed adaptive droop control, section 3.1. elaborating on the current sharing loop, section 3.2. droop shifting calculation, and section 3.3. the additional voltage shifting term; iii) The simulation results are presented in section 4; and iv) Section 5 provides insights from the experimental results.

2. THE DISADVANTAGES OF THE CONVENTIONAL CONTROL METHOD

This section discusses load current sharing and circulating current issues that arise when using parallel DC-DC converters connected to a low-voltage DC microgrid. Figure 2 displays two DC-DC converters connected in parallel to the DC grid. The figure denotes the output voltages, output currents, and cable resistances of converter-1 and converter-2 as $V_{DC1}, V_{DC2}, I_{o1}, I_{o2}, R_{line1}$ and R_{line2}, respectively. The output side of the converter can be represented by a resistor R_{load}, as shown in Figure 2. The primary proportional-integral controller is designed based on the process in [24]. Analysis of system characteristics before and after applying the conventional Droop control method in [19] is presented in detail in the following section.

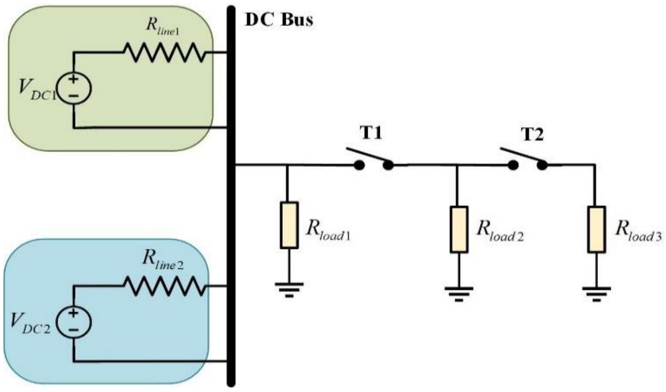


Figure 2. Modeling remote DC microgrid structure in simple form

2.1. Circulating current analysis for the two-converter system

The (1) are established by adopting Kirchoff's voltage law (KVL) to the electrical circuit in Figure 2.

$$V_{DC1} = I_{o1}R_{line1} + R_{load}I_{load}; \quad V_{DC2} = I_{o1}R_{line2} + R_{load}I_{load} \tag{1}$$

From (1), we derive the output voltage of each converter as (2).

$$I_{o1} = \frac{(R_{line2}+R_{load})V_{DC1}\text{-}R_{load}V_{DC2}}{R_{line1}R_{line2}+R_{line1}R_{load}+R_{line2}R_{load}}; \quad I_{o2} = \frac{(R_{line1}+R_{load})V_{DC2}\text{-}R_{load}V_{DC1}}{R_{line1}R_{line2}+R_{line1}R_{load}+R_{line2}R_{load}} \tag{2}$$

Where $R_{load} = R_{load1} + R_{load2} + R_{load3}$. Calculating the current flow from converter-1 to converter-2 by using (2), we obtain (3).

$$\begin{aligned} I_{C12} &= \frac{V_{DC1}\text{-}V_{DC2}}{R_{line1}+R_{line2}} = \frac{I_{o1}-I_{o2}}{2} = \frac{\Delta I_{1,2}}{2} \quad (if\, R_{line1} = R_{line2}) \\ I_{C12} &= \frac{I_{o1}R_{line1}-I_{o2}R_{line2}}{R_{line1}+R_{line2}} \quad (if\, R_{line1} \neq R_{line2}) \end{aligned} \tag{3}$$

Where I_{C12} is the current flowing from the converter-1 to the converter-2, and I_{C21} is the current flowing from converter-2 to the converter-1. Rewriting (2) according to (3), we find these relationships as in (4).

$$I_{o1} = \frac{R_{line2}V_{DC1}}{R_{line1}R_{load}+R_{line2}R_{load}} + \frac{V_{DC1}\text{-}V_{DC2}}{R_{line1}+R_{line2}}; \quad I_{o2} = \frac{R_{line1}V_{DC2}}{R_{line1}R_{load}+R_{line2}R_{load}} + \frac{V_{DC2}\text{-}V_{DC1}}{R_{line1}+R_{line2}} \tag{4}$$

From (4), the output voltage and cable resistance of each converter are found to be the main factors that determine load power sharing performance.

2.2. Load power sharing by conventional droop control method

In this section, we process to analyze the characteristics of the conventional droop control. In Figure 2, the relationship between voltage and current at the output of each converter is expressed as (5).

$$I_{oi} = \frac{V_{nor}-V_{DC\,i}}{R_{droopi}+R_{linei}} \text{(i=1,2)} \tag{5}$$

Where V_{nor}, $V_{DC\ i}$, and $R_{\text{droop}i}$ are reference voltage, voltage on DC bus at the steady-state operating point and virtual resistance presents the droop slope, respectively. According to (5) is the calculates of operating point for each converter and shares the power autonomously in the DC microgrid system. To achieve balance in power sharing, each converter's power output is controlled based on its divergence from the operational point, which is determined using (6).

$$R_{\text{droop}i} \leq \frac{\Delta V_{DC\text{max}}}{I_{oi}^{\text{max}}} \quad \text{with } \Delta V_{DC\ i} = |V_{\text{nor}} - V_{DC\ i}| \leq \Delta V_{DC\ max} \tag{6}$$

Where I_{oi}^{max} is the maximum current that each converter can supply, and ΔV_{DCmax} is the greatest voltage inaccuracy that the system may have when compared with the reference voltage value while the system is in steady state. In other words, (6) assures that the voltage magnitude differences between generators in a DC microgrid are within acceptable limits. This is accomplished by modifying each generator's power output based on its departure from the operational point, resulting in a slight voltage drop in the DC microgrid. Rewriting (3) with (6) yields the voltage difference when power is shared between the two converters as (7).

$$\Delta V_{1,2} = \frac{(R_{\text{droop2}}+R_{\text{line2}})(V_{\text{nor}}\text{-}V_{\text{DC1}})-(R_{\text{droop1}}+R_{\text{line1}})(V_{\text{nor}}\text{-}V_{\text{DC2}})}{(R_{\text{droop1}}+R_{\text{line1}})+(R_{\text{droop2}}+R_{\text{line2}})} \tag{7}$$

The voltage difference in (7) between two converters is controlled by the droop control method in microgrids, which implies that the current sharing between converters is not balanced in the case of two converters having the same capacity. Because the line resistances are always existing in the DC microgrid system, the voltage difference is not eliminated, which leads to inaccurate current sharing.

The unequal load sharing with the conventional method shows in (4) and (7), the blue and orange lines represent small and high droop coefficients, respectively. Increasing $R_{\text{droop}i}$ can cause high error values in the current at the output of the converter ($\Delta I_{1,2} = I_{o1} - I_{o2}$) but only a modest deterioration in DC voltage ($\Delta V_{1,2}$), and vice versa. These limitations reduce the quality of the power supply system, and at the same time have a serious impact on critical devices in remote DC microgrid when the conventional droop is applied.

3. PRINCIPLE OF ADAPTIVE DROOP CONTROL

In this part, we present a novel adaptive droop control strategy that extends the traditional control method and tries to reduce power-sharing error in DC microgrids. The recommended solution incorporates a secondary controller that adaptively modifies the reference voltage, minimizing power-sharing errors between converters. Figure 3 displays a block diagram of the recommended approach, which incorporates the primary and secondary control layers. To analyze this proposed control strategy, we will analyze the primary and secondary control loops.

3.1. The current sharing loop

As mentioned in (7), the voltage error can be minimized by appropriately adjusting the droop gain. Therefore, the final control loop is designed as a current control loop, which is calculated based on the current difference between the converters. A proportional integral controller is used to determine the minimum ΔR_{droop}, while the maximum value is constrained by the reference voltage, and the product of the converter output current and $R_{\text{droop}i}$ must not exceed the maximum allowable voltage deviation. For instance, if the DC voltage is rated at 12 ± 5% V and each converter has a rated current of 5 A, the product of the converter-rated current and $R_{\text{droop}i}$ should be lower than the maximum deviation in the DC bus voltage. The current sharing spread is calculated for i = 2, includes variables $\alpha, b, \eta_i (i = 1,2)$ and is reduced to R_{droop2} calculated by (8) and (9).

$$\Delta I = I_{C12}, \alpha = \frac{V_{\text{DC1}}}{V_{\text{DC2}}}, b = \frac{R_{\text{line1}}}{R_{\text{line2}}} \text{ and } \eta_i = R_{\text{line}i} + R_{\text{droop}i} (i = 1,2) \tag{8}$$

$$I_{\text{o1}} = \frac{-(V_{DC2}-V_{DC1})R_{load}-V_{DC1}\eta_1}{g}; \quad I_{\text{o2}} = \frac{-(V_{DC1}-V_{DC2})R_{load}-V_{DC2}\eta_1}{g} \tag{9}$$

Where $g=1-\frac{R_{load}}{\eta_1} - \frac{R_{load}}{\eta_2}$. From (9), the current sharing difference in (8) is rewritten as (10).

$$\Delta I = \left|\frac{V_{DC1}\eta_2 - V_{DC2}\eta_1}{\eta_1\eta_2 g}\right| \tag{10}$$

Based on (10), the symbol η can be adjusted to address the current sharing difference. Based on the proportional integral controller in Figure 3, we can adjust the $\Delta \mathrm{R}_{\mathrm{droop}i}$ parameter quickly without complicated calculation equations. Then, $V_{DCBus} = V_{Load}$ of the converters can be changed by (11).

$$V_{DCBus} = \mathrm{V}_{\mathrm{nor}} - I_{\mathrm{o\,i}}(R_{\mathrm{droop,i}} + \Delta R_{\mathrm{droop,i}}) \tag{11}$$

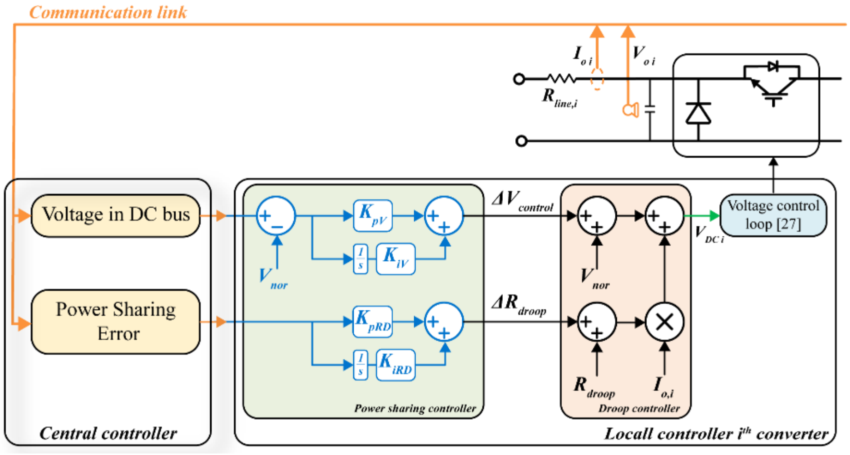


Figure 3. Block diagram of the proposed adaptive droop control approach

3.2. The droop shifting calculation

The initially fixed $R_{\mathrm{droop}i}$ values are not sufficient to balance the load power sharing and make both converter output voltages the same. To improve the power-sharing performance, the droop values must be fine-tuned to regulate the load current sharing between two converters. However, if the $\Delta \mathrm{R}_{\mathrm{droop}i}$ value is always positive according to (11), the voltage on the load will be decreased, and the DC microgrid voltage quality is reduced. To avoid this issue, the proposed control method in this study calculates the $R_{\mathrm{droop}i}$ value by considering the sign of ΔI, which is calculated by (10).

The process of $R_{\mathrm{droop}i}$ shifting involves comparing the output current of two converters and adjusting the value of $R_{\mathrm{droop}i}$ accordingly. In the case where the output current of one converter is greater than the other, the value of $R_{\mathrm{droop}i}$ for the lower current converter is decreased to achieve equal current sharing. This bias adjustment leads to improved load sharing and microgrid voltage. The algorithm for $R_{\mathrm{droop}i}$ shifting can be summarized below as in equation.

If the current deviation, i.e., ΔI is positive, then the new droop gain values $R_{\mathrm{droop}i_{\mathrm{new}}}(i = 1{,}2)$ are given as (12).

$$R_{droop1_{new}} = R_{droop1} - \Delta R_{droop}; \quad R_{droop2_{new}} = R_{droop2} + \Delta R_{droop} \tag{12}$$

If ΔI is negative, then the new droop gain value $R_{\mathrm{droop,i}_{\mathrm{new}}}(i = 1{,}2)$ is given as (13).

$$R_{droop1_{new}} = R_{droop1} + \Delta R_{droop}; \quad R_{droop2_{new}} = R_{droop2} - \Delta R_{droop} \tag{13}$$

If ΔI is zero, then the new droop gain value $R_{\mathrm{droop,i}_{\mathrm{new}}}(i = 1{,}2)$ is the same as the previous values and is given as (14).

$$R_{droop1_{new}} = R_{droop1}; \quad R_{droop2_{new}} = R_{droop2} \tag{14}$$

The previous values of the droop, R_{droop1} and R_{droop2}, are modified after shifting $R_{\mathrm{droop}i}$ to obtain new droop values, $R_{\mathrm{droop1}_{\mathrm{new}}}$and $R_{\mathrm{droop2}_{\mathrm{new}}}$, respectively, as demonstrated in (12)–(14). The improvement in converter output and load voltages is attributed to this proposed droop modification.

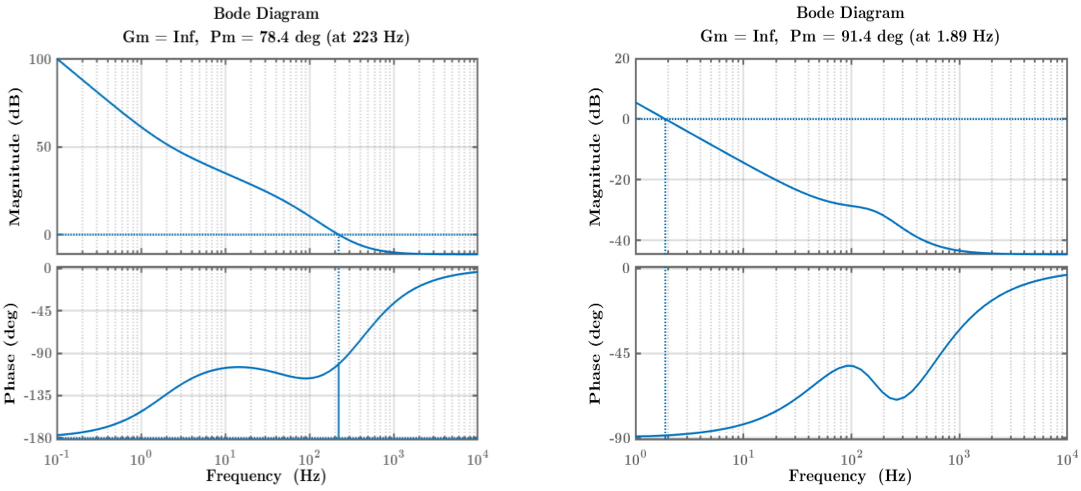
3.3. The additional voltage shifting term

To decrease the mistake while sharing power across generators in the DC microgrid, the secondary control loop computed optimal shirt resistance values. However, the aforementioned control loop cannot address the issue of voltage difference between generators since signal (ΔR_{droop}) simply calculates the adjustment of current sharing between converters. Therefore, we add a control loop parallel to the power loop in the secondary controller to reduce the voltage variance between the generator and the DC bus.

This controller has the purpose of calculating the voltage control signal ($\Delta V_{control}$) and adding it to the secondary control loop. Each generator controller in the microgrid is responsible for restoring the DC bus voltage to its nominal value. The updated reference voltage then bears as (15).

$$V_{\mathrm{DC}i}=\Delta \mathrm{V}_{\mathrm{control}}+V_{\mathrm{nor}}-I_{oi}(R_{\mathrm{droop}i}+\Delta R_{\mathrm{droop}}) \tag{15}$$

By considering the voltage shifting $\Delta V_{control}$, the output voltage of each converter adjusts its value intending to increase the DC microgrid voltage, so that the voltage drop caused by the conventional control method is mitigated and voltage quality is improved. The proportional integral parameters of the secondary controller are designed so that the controller bandwidth is set as $1/10$ of the primary control loop for ensuring system stability [25], [26]. The bode diagram of secondary voltage and current controllers is shown in Figure 4, with a phase margin higher than 60° to ensure control performance [27].



(a) (b)

Figure 4. Bode diagram of secondary droop controller: (a) current sharing loop and (b) DC bus voltage loop

4. SIMULATION RESULTS

In this study, we utilized the PLECS software to simulate an adaptive control technique for DC microgrids with two converters and multiple load scenarios. We decreased the DC microgrid system's voltage to 12 V in the laboratory for safety considerations, assuring a controlled environment while yet offering a fair basis for evaluating the performance of the actual DC microgrid. The resister load also reveals the power consumption of important components with varying load power levels, which is used to evaluate system responsiveness. To assist the evaluation of controller efficiency, the power of the two sources is believed to be equal, and the input power is not varied during the simulation execution time. In the first simulation scenario, the conventional droop control method is adopted in the microgrid system with only load 1 $R_{load1} = 5\Omega$ during $0\ s \leq t < 2\ s$. At $t = T1 = 2s$, load 2 with $R_{load2} = 20\Omega$ is suddenly connected to the system to evaluate the voltage drop and current sharing performance.

In the second simulation scenario, the proposed adaptive control method is adopted $t = 1s$ to improve the current sharing performance and voltage quality. Then, load 2 is connected to the system at $t = 2\ s$. After proving that the proposed control method has better performance than the conventional one, the additional load 3 with $R_{load3} = 12\Omega$ at $t = T2 = 3\ s$ is connected to the microgrid to test the system's reliability and stability. Figure 2 shows the simplified microgrid model used in the first simulation scenario, and the microgrid parameters are shown in Table 1.

Table 1. System parameters

Parameter	Symbol	Values
Ideal voltage DC bus	V_{nor}	12 V
Load 1, 2, and 3	R_{load1}, R_{load2}, R_{load3}	$5\Omega, 20\Omega, 12\Omega$
Line resistance	R_{line1}, R_{line2}	$0.2\Omega, 0.25\Omega$
Secondary voltage controller parameters	K_{pV}, K_{iV}	1, 10
Secondary current sharing controller parameters	K_{pRD}, K_{iRD}	0.005, 0.01

4.1. The first simulation scenario: performance of the conventional control method

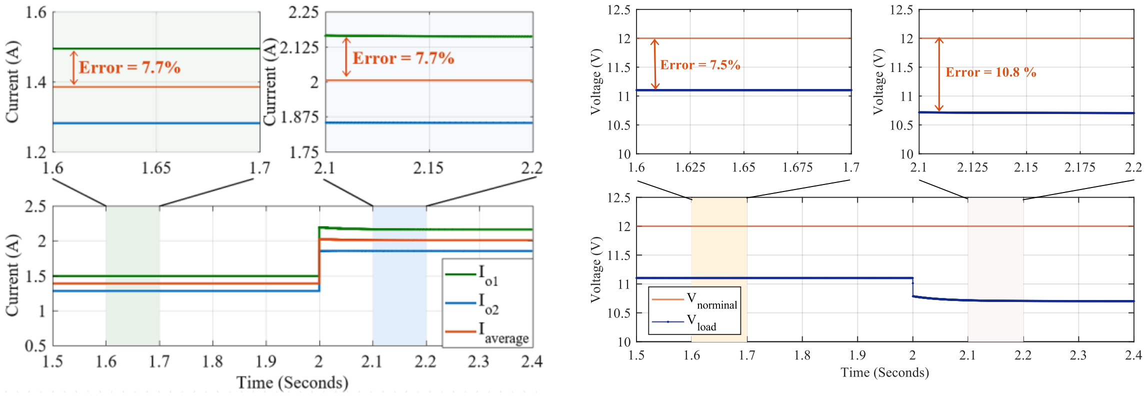
The study evaluated the performance of the conventional droop controller, and the voltage and current sharing performance is shown in Figure 5. In Figure 5, the currents are shared autonomously between two converters, and currents are increased when load 2 is connected to the system at $t = 2\ s$. Also, the converter voltages are smaller than that of the nominal value (12 V) with a 7.5% voltage error. Although the load currents are not shared proportionally between converters with a 7.7% current sharing error, the conventional droop control still maintains an autonomous current sharing in the DC microgrid. When load 2 is connected to the system, the voltage error is increased to 10.8% but the current sharing error remains unchanged at 7.7%. Even though the load represented by the critical device can be shared autonomously between converters, inaccurate current sharing, and high voltage deviation are the main issues of the conventional control method.

4.2. The second simulation scenario: performance of the proposed adaptive control method

Figure 6 shows current sharing during the transient period when the proposed current sharing term is activated. According to Figure 6(a), it can be observed that during the time interval from $t = 0\ s$ to $t = 1\ s$, there is an unequal distribution of output current between the two shared converters with a 7.7% current sharing error. This is consistent with what was observed in (3) and (4) that the output current always depends on the line resistance.

By applying the proposed adaptive control method at $t = 1\ s$, the drop gain is utilized so that the current sharing is improved gradually. The equal current sharing is obtained after $t = 1.2\ s$, with a 0.01% current sharing error, as shown in Figure 6(a). Figure 6(b) shows microgrid voltage performance using the proposed adaptive control method. When the proposed method is activated, the microgrid voltage increases to the reference voltage, and the voltage deviation is minimized. Regardless of the R_{droop} value, the voltage deviation on the bus remains constant. This stable voltage on the bus is a crucial factor in ensuring the proper operation of critical devices.

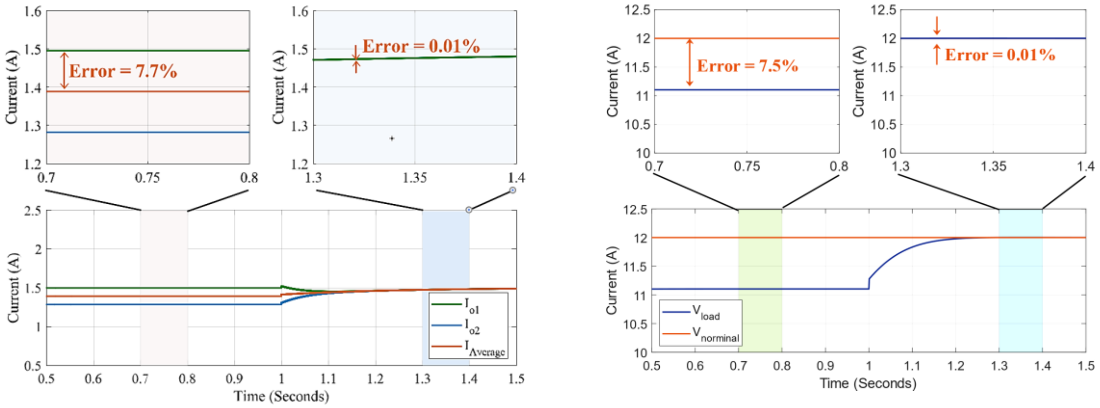
In the case when the load is changing, we evaluate the system performance when additional load 3 is connected to the system at $t = 2.5\ s$ and is disconnected at $t = 3\ s$ to emulate the microgrid voltage overshoot and test the effectiveness of the proposed controller. Figures 7(a) and 7(b) show the output currents and voltages of the proposed control method with different load conditions. The corresponding current sharing error and voltage error at the load are calculated and shown in Figure 8.



(a) (b)

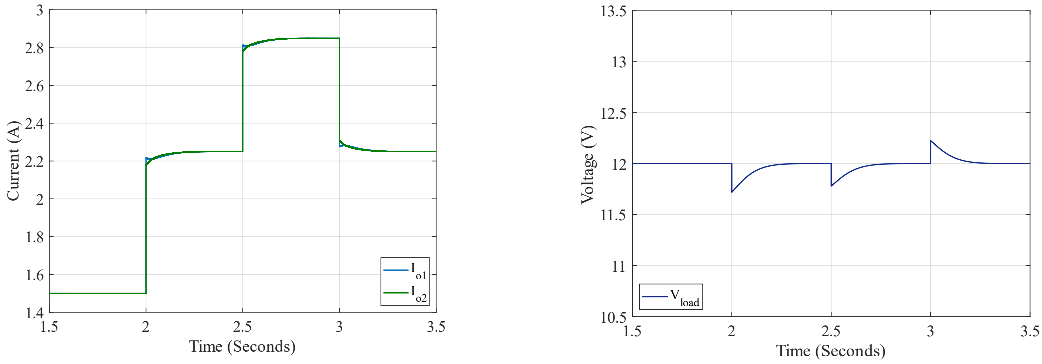
Figure 5. The output currents and voltages of the conventional droop controller: (a) current sharing performance and (b) voltages of two converters

The simulation results in Figure 7(a) and Figure 8(a) indicate that the proposed droop controller has properly shared the current between the two converters, with a small current sharing error. Whenever the load changes, the proposed controller compensates for the voltage drop in the microgrid by increasing the output voltage of each converter, as shown in Figure 7(b) and Figure 8(b). As a result, the voltage error ($V_{error} = V_{nor} - V_{load}$) is very small. Even though load 3 is connected to the microgrid at $t = 2.5\ s$ and $t = 3\ s$, the voltage deviation is still kept at zero-voltage value. From the simulation results in Figure 7 and Figure 8, it can be concluded that the proposed adaptive control method works well regardless of load condition changes.



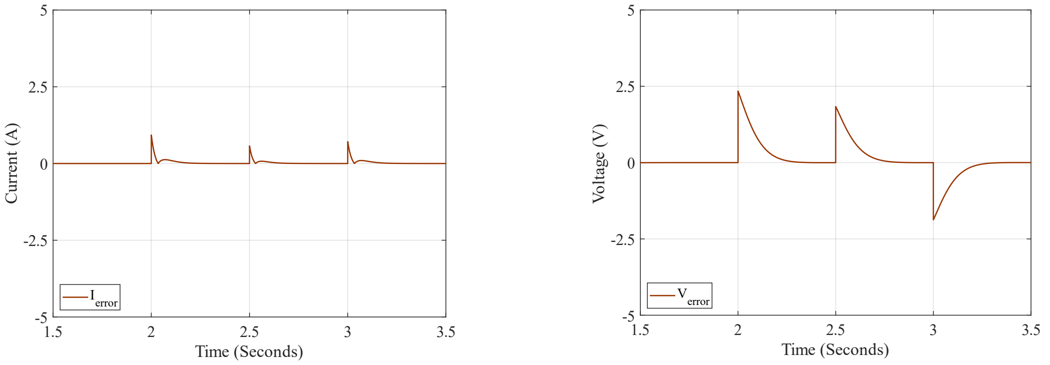
(a) (b)

Figure 6. The output currents and voltages when applying the proposed control method: (a) current sharing performance and (b) voltages of two converters



(a) (b)

Figure 7. The output currents and voltages of the proposed control method with different load conditions: (a) current sharing performance and (b) voltage at the load



(a) (b)

Figure 8. The current sharing error and voltage error at the load of the proposed control method with different load conditions: (a) current sharing error and (b) voltage error at the load

5. EXPERIMENTAL RESULTS

The suggested adaptive control method's experimental efficacy is assessed using a laboratory DC microgrid model. The implementation of a 12 V scale-down microgrid model promotes laboratory safety while also offering a realistic and trustworthy basis for testing the microgrid system. Figure 9 displays a scaled-down laboratory DC microgrid that contains a microcontroller, monitoring computer, voltage probe, current probe, DC-DC converter, and other laboratory gear.

In this system, the DC bus voltage reference is set as 12 V, two DC-DC buck converters are connected in parallel to the DC bus, and the line resistance mismatches are considered in the proposed controller. Three changes of the load resistance are made through the DC programable load IT8512A with R_{load} varying from 5Ω to 3Ω. Initially, the conventional droop is adopted, and the proposed voltage shifting term is activated to enhance the DC voltage quality. At $t = T1$, the proposed current sharing term is activated to correct the current sharing between two converters. The total load resistance is reduced from 5Ω to 4Ω at $t = T2$, and from 4Ω to 3Ω at $t = T3$. At $t = T4$, the total load resistance is increased from 3Ω to 5Ω.

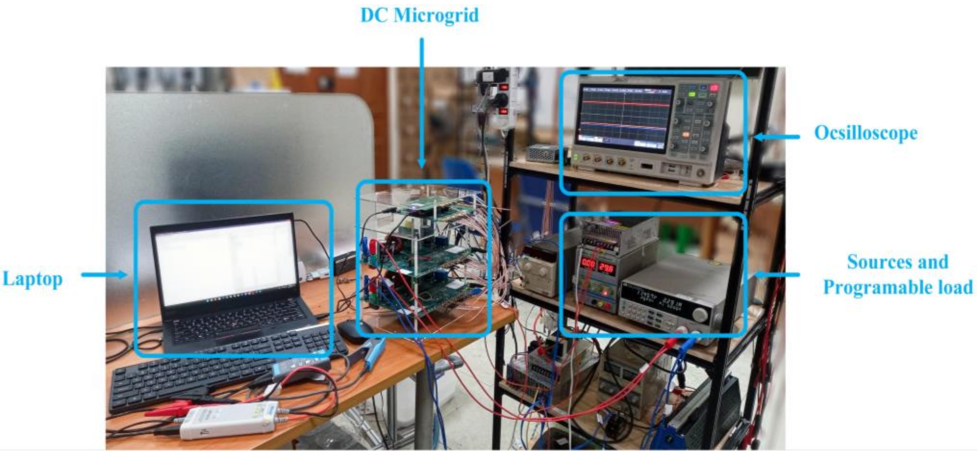


Figure 9. A laboratory DC microgrid model is used to perform out experiments

Figure 10 shows the DC bus voltage and two converter currents during the transient period when the proposed current sharing term is activated. Before activating the proposed current sharing term ($t < T1$), there is a difference in converter output current because the conventional droop controller does not consider the effect of line resistance. When the proposed current sharing is enabled at $t = T1$, the two converters adaptively adjust their currents, and their output currents convert to the ideal current value after a short transient time of 500 ms. By adopting the proposed adaptive control method, equal current sharing is obtained, and its performance is maintained without oscillation in the steady state.

In addition, the DC bus voltage is kept constant at a nominal value of 12 V during the current adjustment of the two converters, as we can see in the red line in Figure 11. This result shows the proposed voltage shifting term works well to ensure a high voltage quality without voltage oscillation for the critical load. To evaluate the proposed control method under different load conditions. The total load resistance is changed from 5Ω to 4Ω, and the result is shown in Figure 11(a). Even though the load changes suddenly, the additional currents are properly regulated, and the DC voltage is ensured without any voltage drop thanks to the proposed control method.

Another test to verify the system stability is to change the total load resistance from 4Ω to 3Ω, as shown in Figure 11(b). In this condition, both current sharing performance and microgrid voltage maintain their reference values. In two cases of changing load resistances in Figure 11(a) and Figure 11 (b), there are small oscillations in output current and microgrid voltage, but it is negligible (<1%) and does not affect the critical load.

In the opposite circumstance, a sudden drop in load current consumption serves as a test for the proposed control effectiveness. Figure 11(c) demonstrates current sharing efficiency and voltage quality during load increase from 3Ω to 5Ω. When the current drops suddenly, an overshoot in the DC microgrid appears and it is unavoidable, as shown in Figure 11(c). However, thanks to the proposed control method, the voltage overshoot is shortly attenuated, and the microgrid voltage tracks its reference properly in the steady state.

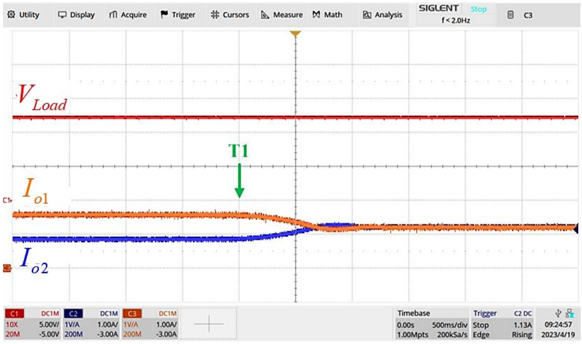
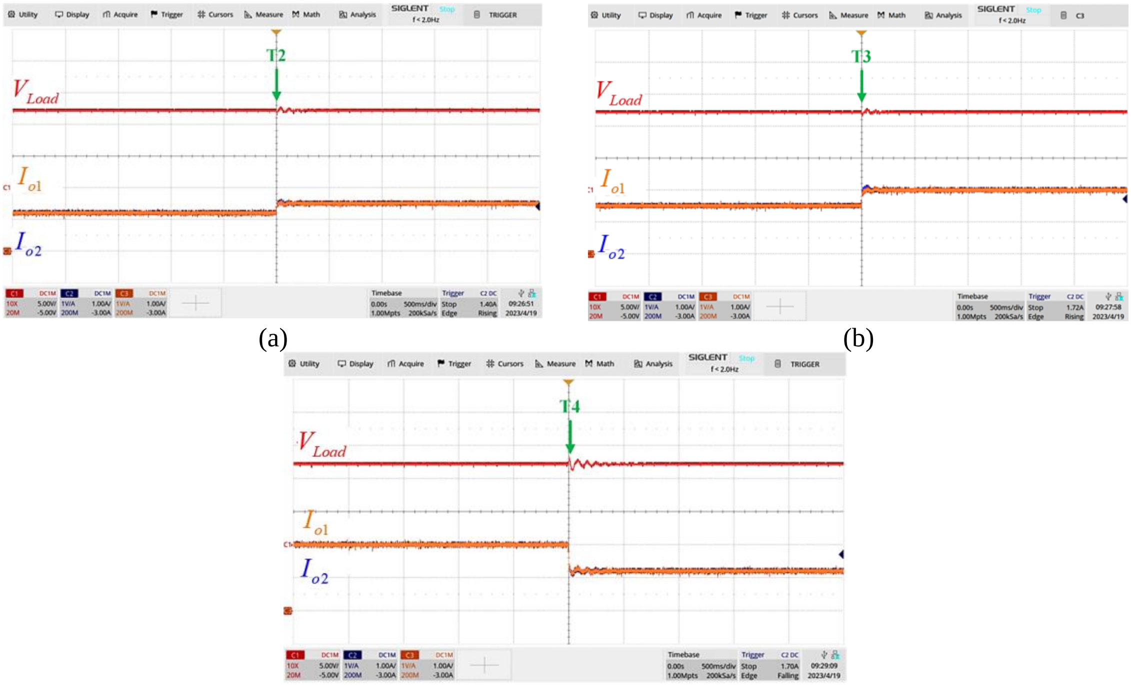


Figure 10. Performance of the two converters when enabling the proposed droop control method



(a) (b)

(c)

Figure 11. Performance of the two converters using the proposed adaptive droop control when R_{load} changes: (a) 5 Ω to 4 Ω; (b) 4 Ω to 3 Ω; and (c) 3 Ω to 5 Ω

6. CONCLUSION

The proposed adaptive control method for remote DC microgrids has shown great potential in improving the reliability and stability of critical devices. The method offers several advantages over conventional control strategies, including better power quality, enhanced reliability, and higher voltage efficiency. Through various simulations and experiments, it has been demonstrated that adaptive control methods can effectively address the challenges of voltage deviation and load changes in the DC microgrid. In the proposed adaptive control method, the output currents are fed back to calculate the appropriate droop gain for improving current sharing performance. In addition, the additional voltage shifting term is calculated with the proposed control method so that the microgrid voltage deviation is minimized. By adopting the proposed method, the voltage quality is improved with a small ripple, and its performance is ensured despite load condition changes. As a result, a stable and reliable power supply to critical critical devices is ensured.

It is important to note that the proposed method also has some limitations. In particular, the performance of the adaptive control methods may be affected by the accuracy of the sensor measurements, the communication delays in the network, and the presence of faults or disturbances. Nevertheless, with further research and development, the adaptive control methods for remote DC microgrids have the potential to provide a more stable and secure power supply for critical devices and improve the overall quality of remote DC microgrids.

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