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Off-Grid Smoothing Control Strategy for Dual Active Bridge Energy Storage System Based on Voltage Droop Control

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Abstract: Energy storage systems based on dual active bridge (DAB) converters are a critical component of DC microgrid systems. To address power oscillations and system stability issues caused by power deficits during the off-grid operation of DC microgrids, a control strategy for DAB energy storage systems based on voltage droop control is proposed. By analyzing the internal operational mechanisms of DAB power electronic converters and integrating voltage droop equations, a small-signal model is constructed to deeply investigate the dynamic characteristics of DAB energy storage systems under off-grid conditions. Using the Nyquist stability criterion, appropriate voltage droop coefficients are selected to enhance system stability. Finally, a DC microgrid model is built on the MATLAB/Simulink simulation platform. Through the rational design of the droop coefficients, the overshoot of the power response is reduced from 28.87% to 4.27%, and settling time is effectively shortened while oscillations are suppressed. The simulation results validate the correctness and effectiveness of the theoretical framework proposed in this study.

Keywords: DC microgrid; dual active bridge topology; droop control; small-signal model; power fluctuations; Nyquist stability



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1. Introduction

As global fossil fuel resources are gradually depleting, renewable energy technologies such as wind power and photovoltaics are receiving increasing attention from both academia and industry. Compared to AC distribution networks, DC microgrid systems can effectively improve power quality, reduce the use of power electronic converters, lower energy losses and operational costs, and help resolve conflicts between the large power grid and distributed energy sources (DERs), fully realizing the value and benefits of distributed energy sources [1–9].

Unlike AC grids, DC microgrids are low-inertia systems, and the DC bus voltage is sensitive to the integration of renewable energy, load changes, and the transition between grid-connected and off-grid modes. Particularly during off-grid transitions, the microgrid loses the stability provided by the main grid, and the microgrid itself must minimize power deficits that occur instantaneously during off-grid switching. Therefore, a suitable control strategy is necessary to improve the stability of the DC microgrid during off-grid transitions and to enhance power quality. In DC microgrid operation, energy storage systems are typically installed to provide inertial power support during off-grid transitions, improving power quality [10]. The dual active bridge (DAB) topology, which features high power density, soft switching, bidirectional power flow capability, and ease of cascading and parallel operation, is widely used in energy conversion and storage in DC microgrids.

Droop control is one of the most commonly used strategies in DC microgrid systems. In [11,12], the authors proposed a hybrid energy storage control strategy based on voltage droop control in DC microgrids, which can reduce bus voltage fluctuations. In [13,14], the authors proposed a novel adaptive voltage inertia control method using a virtual machine, which avoids voltage transients in the initial stage of disturbances by modifying the voltage outer loop, though the power electronic converter topology analyzed is a bidirectional Buck/Boost topology [11,12]. The authors of [15] proposed an adaptive virtual DC machine control method for DAB converters in DC grids, which can provide good dynamic power support during voltage sags, but the fuzzy control scheme used lacks systematicity, and it is difficult to generalize it into mathematical formulas for promotion. The authors of [16,17] considered the potential inertial support capabilities of various rotating devices and energy storage equipment in DC microgrids, proposing a virtual inertia control strategy for DC microgrids. However, it takes an overall power system perspective and does not fully consider the internal phase shift mechanism of DAB power electronic devices, making it difficult to tune the parameters for a single converter topology. The authors of [18] experimentally quantified the efficiency impacts of different droop curves, revealing relationships between droop characteristics, soft-switching conditions, circulating currents, and dead-time effects. The authors of [19] proposed an adaptive droop method with virtual rated power for multi-ESS islanded systems, using an arctangent function to dynamically adjust droop coefficients for rapid state-of-charge (SOC) balancing and line impedance mismatch compensation. Three-phase phase shift control strategies [20–22] were developed to optimize reactive power in DAB converters by reducing inductor currents through phase shift angle adjustments.

To address these issues, this paper proposes an off-grid smoothing control strategy for a DAB energy storage system based on voltage droop control. By analyzing the operating principles of the DAB topology, a small-signal model of the DAB topology is constructed for off-grid moments. The relationship between the coefficients in the voltage droop equation, the power deficit, and the stability of the DC microgrid is analyzed, and a reasonable range for selecting the droop coefficient is calculated. The overall control scheme is simple and feasible, and it can provide greater stability for the DC microgrid during off-grid moments, smoothing the power deficit that occurs during off-grid switching. Finally, simulations verify the theoretical validity and effectiveness of the proposed control strategy.

In this article, Section 2 establishes the mathematical model of the DC microgrid system and DAB energy storage converter, deriving the small-signal transfer function of the DAB based on the reduced-order model and constructing the control block diagram incorporating the voltage droop equation. Section 3 employs the Nyquist stability criterion to analyze the quantitative relationship between the droop coefficient and system stability during off-grid transitions, proposing a tuning method for the droop coefficient. Section 4 verifies the dynamic response characteristics of the proposed control strategy under different power deficits and droop coefficients through simulations on the MATLAB/Simulink platform (R2023a).

2. DC Microgrid System and Internal Structure

The DC microgrid system mainly consists of distributed renewable energy generation units (including photovoltaic power generation and wind power generation), power electronic conversion devices, energy storage units, and electrical loads. To enhance system stability, the system can be interconnected with the external main grid through a grid connection point. Figure 1 shows the typical structure of a DC microgrid system.

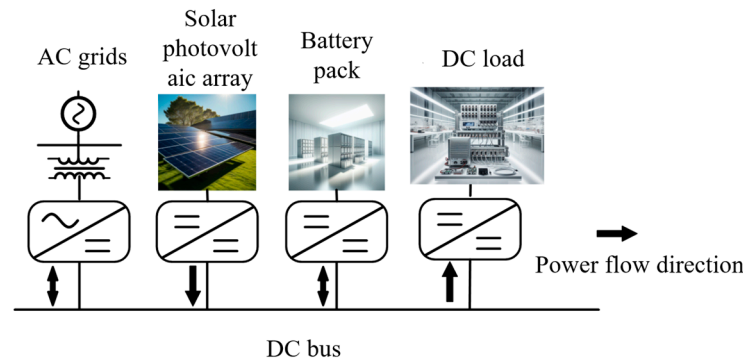


Figure 1. DC microgrid system diagram.

The photovoltaic generation array is connected to the DC bus through a Boost converter, the battery pack is connected to the bus through a DAB converter, and the DC loads are connected to the bus via DC/DC converters. In grid-connected mode, the external main grid is responsible for maintaining the stability of the DC bus voltage, while the distributed renewable energy generation system operates in maximum power point tracking (MPPT) mode. The battery energy storage system determines charge and discharge operations based on its state of charge (SOC) and the grid conditions. In off-grid mode, the control of the DC bus voltage shifts from the main grid to the energy storage system. This study aims to explore the performance of DC microgrids during the off-grid transition. It is assumed that the energy demand of the load exceeds the supply capacity of the photovoltaic system, meaning that before the system goes off-grid, part of the energy is supplied by the external grid to maintain the bus voltage. After going off-grid, the energy storage system compensates for the power deficit and provides the necessary inertial power support to the microgrid system.

2.1. Mathematical Model of Energy Storage Side DAB-Type DC-DC Converter

A topology diagram of the dual active bridge (DAB) power electronic converter used in the battery pack is shown in Figure 2. It consists of a high-frequency transformer with a ratio of $n:1$, full-bridge switches on both the primary and secondary sides, an inductor L_b , and filter capacitors C_1 and C_2 on both sides. Switches $S_1 \sim S_4$ correspond to the full-bridge switches on the primary side (battery side), while switches $S_5 \sim S_8$ correspond to the full-bridge switches on the secondary side (DC bus side). u_c represents the voltage on the energy storage battery side, u_{dc} represents the voltage on the DC bus side, i_{b1} is the current flowing into the DAB on the primary side, i_{b2} is the current flowing out of the DAB on the secondary side, and I_{out} is the current flowing from the DAB into the microgrid.

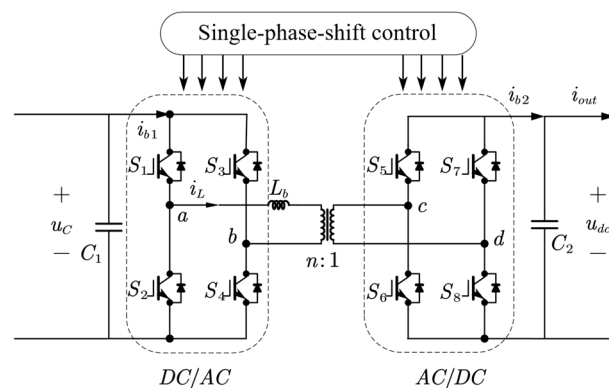


Figure 2. Dual active bridge (DAB) topology diagram.

The control method used is the single-phase-shift modulation strategy. The drive signals for the full-bridge circuits on both the primary and secondary sides are square wave signals with a 50% duty cycle. By adjusting the phase shift between the primary and secondary full-bridges, the DAB output voltage is controlled.

Compared with conventional bidirectional DC-DC converters, the inductor current, i_L , inside the DAB contains high-frequency AC components, and the DC component remains zero over a complete switching cycle. This makes traditional average-switch-cycle modeling methods unsuitable for the DAB topology. To address this modeling challenge, the academic community has proposed various methods, including reduced-order models [23–25], generalized average models [26–28], and discrete-time models [29–32], to accurately describe the dynamic response characteristics of the DAB topology. Among them, the reduced-order model ignores the dynamic variations in inductor current. Compared with other models, the reduced-order model is simpler in structure and offers excellent modeling accuracy [33,34].

Therefore, this study adopts the reduced-order model to construct the mathematical model of the DAB topology. The basic principles of the reduced-order model are as follows:

1. By calculating the average value of the input and output currents over one switching cycle, the high-frequency variations in the primary and secondary side currents are equivalent to a current source.
2. The dynamic responses of components, including the primary and secondary side capacitors, the power supply, and the load, are taken into account and integrated into the topology. This approach simplifies the characteristics of the DAB converter to a first-order system model. The simplified structure is illustrated in Figure 3.

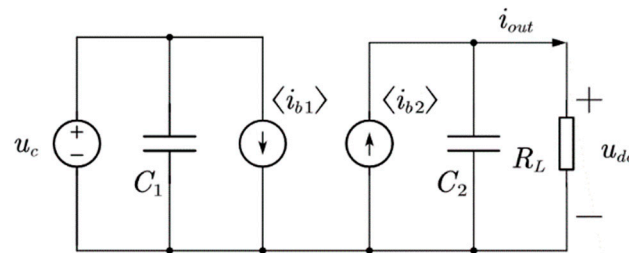


Figure 3. Reduced-order model of DAB topology.

In Figure 3, i_{b1} and i_{b2} represent the average values of the currents over a switching cycle, and R_L is the equivalent DC load.

2.1.1. Operating Principle of DAB Topology

The working principle of the dual active bridge (DAB) converter is equivalent to constructing two high-frequency DC/AC systems. Power transmission occurs due to the phase shift between these systems. The transmitted power is given by the following:

$$P = \frac{nu_c u_{dc} \phi (1 - 2|\phi|) T_s}{L_b} \quad (1)$$

where ϕ represents the phase shift ratio under steady-state operating conditions, the principal value interval of ϕ is $(-1/4 < \phi < 1/4)$, and T_s is the switching period of the DAB system.

According to the reduced-order model of Figure 3, the transmitted power in the DAB under normal operation is expressed as follows:

$$P = u_{dc} \langle i_{b2} \rangle \quad (2)$$

$\langle i_{b2} \rangle$ represents the current of the secondary side in steady-state operating conditions.

Because the power moves in the forward direction during the off-grid moment, $\langle i_{b2} \rangle$ is positive, and the phase shift ratio ϕ is also positive. By substituting Equation (2) into Equation (1), the magnitude of the secondary side current source can be obtained as follows:

$$\langle i_{b2} \rangle = \frac{nu_c \phi (1 - 2\phi) T_s}{L_b} \quad (3)$$

To derive the transfer function between the phase shift angle and the secondary side current, the perturbations of both the phase shift angle and the current are added:

$$\begin{aligned} \phi &= \Phi + \Delta\phi \\ \langle i_{b2} \rangle &= I_{b2} + \Delta i_{b2} \end{aligned} \quad (4)$$

In (4), Φ and I_{b2} represent the phase shift angle and current in the steady state, respectively. Meanwhile, $\Delta\phi$ and Δi_{b2} represent small disturbance signals at the steady-state operating point.

Substituting Equation (4) into Equation (3), the small-signal transfer function between the phase shift angle and the secondary side current can be obtained as follows:

$$G_{\phi i}(s) = \frac{\Delta i_{b2}}{\Delta\phi} = \frac{d\langle i_{b2} \rangle}{d\Phi} = \frac{nu_c (1 - 4\Phi) T_s}{L_b} \quad (5)$$

Under steady-state conditions $I_{b2} = i_{out} = \frac{U_{dc}}{R_L}$, combining with Equation (3), the phase shift angle between the primary and secondary sides of the DAB in the steady state can be calculated as follows:

$$\Phi = \frac{1}{4} - \sqrt{\frac{1}{16} - \frac{L_b i_{out}}{2nu_c T_s}} \quad (6)$$

Using Equation (6), the phase shift angle in the steady state Φ can be pre-calculated as the set value ϕ^* for phase shift control. Therefore, a phase shift feedforward strategy can be used to improve the dynamic response of the DAB topology. A control block diagram of the DAB is shown in Figure 4, where PI represents the voltage proportional–integral control element.

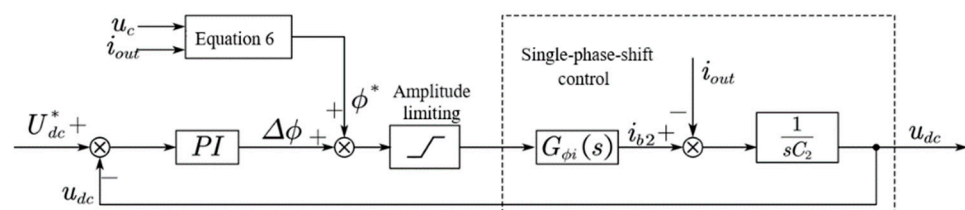


Figure 4. Control block diagram of DAB system.

2.1.2. A DC Droop Control Strategy for the Energy Storage Side DAB-Type DC-DC Converter

To enhance the stability of the microgrid after the energy storage system is connected, the DAB energy storage system needs to use a DC droop control strategy to compensate for power shortages in off-grid conditions. The I-U curve of droop control is shown in Figure 5.

In Figure 5, U_0 represents the intercept of the I-U droop curve, which is typically the rated grid voltage. U_h and U_l denote the upper and lower limits of the DC bus voltage operation. According to IEC-60038 standards, the operating voltage deviation is typically $\pm 10\%$ of the nominal voltage, which means $U_h = 1.1U_0$, and $U_l = 0.9U_0$. In Figure 5, I_{lim}

and I_{hlim} represent the maximum charge and discharge currents during DAB operation. From Figure 5, the DC voltage reference for the DAB can be derived as follows:

$$U_{dc}^* = U_0 - ki_{out} \quad (7)$$

In the DC droop control strategy, the parameter k is slope of the I-U droop curve, and its dynamic characteristic during control can be approximated as a virtual resistance. When the DC bus voltage rises above the set value U_0 , the DAB system absorbs the excess power from the DC bus to stabilize the voltage. Conversely, when the voltage drops below U_0 , the DAB system releases power to fill the bus power deficit and maintain voltage balance. If DC bus voltage exceeds the limits of U_h and U_l , it indicates that the DAB system has reached its maximum power output. In such cases, the load needs to be adjusted for power demand on the DC bus side in order to further stabilize the system.

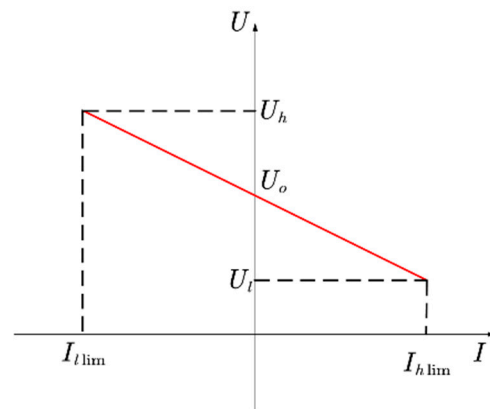


Figure 5. DC I-V droop curve.

When using DC droop control, the power transmitted by the DAB is as follows:

$$P^* = U_{dc}^* i_{out} = (U_0 - ki_{out}) i_{out} \quad (8)$$

By substituting Equations (7) and (8) into Equation (1), the required phase shift angle for the DAB under the DC droop control strategy is calculated as follows:

$$\phi_{droop}^* = \frac{1}{4} - \sqrt{\frac{1}{16} - \frac{(U_0 - ki_{out})L_b i_{out}}{2nu_c u_{dc} T_s}} \quad (9)$$

According to Equation (9), the DAB control block diagram using the droop control strategy changes from Figure 4 to Figure 6.

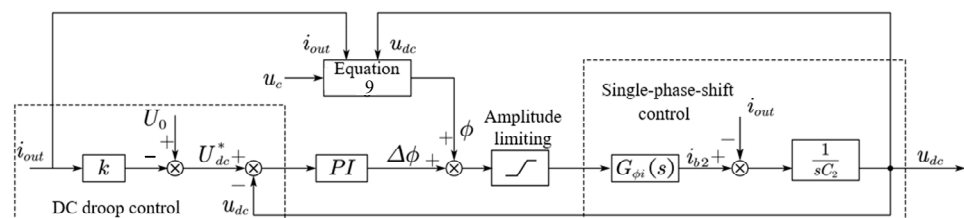


Figure 6. Droop control-based DAB control block diagram.

3. Small Signal Stability Analysis in DAB

The small-signal stability analysis method is an effective way to evaluate the stability of power electronic converter topologies, and small-signal modeling is the foundation of small-signal stability analysis. This section constructs a small-signal analysis model of the

DAB converter by assessing the specific perturbations in the primary side voltage, output current, and phase shift angle on the output voltage under steady-state working conditions. This allows us to explore the effects of the DAB's DC droop control strategy on the stability and dynamic response characteristics of the microgrid system.

During actual operation, neglecting internal energy losses in the DAB converter, power transmission between the primary and secondary sides is in a balanced state:

$$u_c i_{b1} = u_{dc} i_{out} \quad (10)$$

Performing a small-signal linearization analysis on Equation (10) at steady state, introducing perturbations and neglecting higher-order terms, yields the following:

$$U_c \Delta i_{b1} + \Delta u_c I_{b1} = U_{dc} \Delta i_{out} + \Delta u_{dc} I_{out} \quad (11)$$

where Δi_{b1} , Δu_c , Δi_{out} , and Δu_{dc} represent the perturbations in the input current on the DAB energy storage side i_{b1} , input voltage on the energy storage side u_c , output current on the grid side i_{out} , and output voltage on the grid side u_{dc} , respectively. I_{b1} , U_c , I_{out} , and U_{dc} represent the steady-state values of the corresponding variables.

To analyze the transfer function between the grid-side output current i_{out} and the grid-side voltage u_{dc} , we neglect Δi_{b1} and Δu_c and apply a Laplace transform to Equation (11):

$$G_{iv}(s) = \frac{\Delta u_{dc}}{\Delta i_{out}} = -\frac{U_{dc}}{I_{out}} \quad (12)$$

Similarly, the transfer function between the energy storage side voltage u_c and the grid-side voltage u_{dc} is as follows:

$$G_{v1}(s) = \frac{\Delta u_{dc}}{\Delta u_c} = \frac{I_{out}}{I_{b1}} \quad (13)$$

Based on the DAB mathematical model constructed in Section 2.1 and the control transfer function block diagram, it is assumed that, under steady-state conditions, the DAB does not trigger the constraints of the amplitude limiting circuit. Combining Figure 6 with Equations (12)–(14), a linearized small-signal analysis is performed, resulting in the DAB topology small-signal model shown in Figure 7.

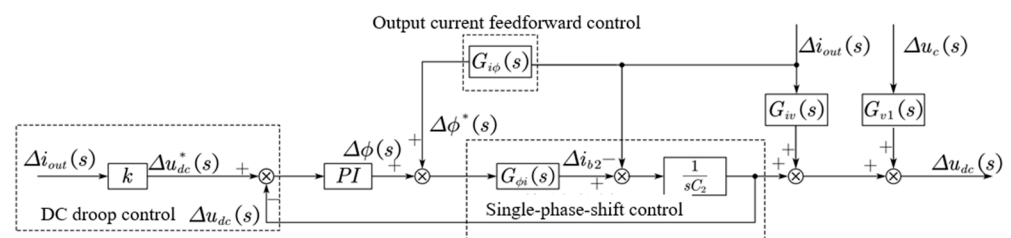


Figure 7. Small-signal model of droop control-based DAB.

In Figure 7, $G_{\phi i}(s)$, $G_{iv}(s)$, and $G_{v1}(s)$ correspond to Equations (5), (12), and (13), respectively. $G_{\phi}(s)$ represents the voltage PI controller, where $G_{\phi}(s) = k_{p\phi} + k_{i\phi}/s$.

Equation (9) is the phase shift feedforward control equation, which in the small-signal block diagram is equivalent to the feedforward control transfer function of the output current $G_{i\phi}(s)$, and its value is the partial derivative of the phase shift angle with respect to the output current from Equation (9):

$$G_{i\phi}(s) = \frac{d\phi^*}{di_{out}} = \frac{(U_0 - 2ki_{out})L_b}{4nu_c u_{dc} T_s A} \quad (14)$$

where

$$A = \sqrt{\frac{1}{16} - \frac{(U_0 - k i_{out}) L_b i_{out}}{2 n u_c u_{dc} T_s}} \quad (15)$$

According to the small-signal model, the small-signal open-loop transfer function $TF(s)$ between Δu_{dc} and $-\Delta i_{out}$ is as follows

$$\begin{aligned} TF(s) &= -\frac{\Delta u_{dc}(s)}{\Delta i_{out}(s)} = -(G_{\phi i}(s) G_{\phi}(s) k / s C_2 + G_{i\phi}(s) G_{\phi i}(s) / s C_2 - 1 / s C_2) \\ &= -\frac{n u_c k (1-4\Phi) T_s k_{p\phi}}{L_b s C_2} - \frac{n u_c k (1-4\Phi) T_s k_{i\phi}}{L_b s^2 C_2} - \frac{(U_0 - 2k i_{out})(1-4\Phi)}{4 u_{dc} \sqrt{\frac{1}{16} - \frac{(U_0 - k i_{out}) L_b i_{out}}{2 n u_c u_{dc} T_s}} s C_2} + \frac{1}{s C_2} \end{aligned} \quad (16)$$

Assuming a power deficit occurs at the moment of going off-grid, the DAB energy storage system needs to compensate for this deficit to maintain the stability of the DC bus voltage, resulting in a positive DAB output current. On this basis, the droop coefficient k is set to 0, and the stability of the DAB energy storage system is analyzed under different power deficit conditions using the Nyquist stability criterion. The system parameters are specified according to Table 1. Figure 8 shows the Nyquist plot of $TF(s)$ under different DAB output power levels. From Figure 8, it is evident that with the power increases, the Nyquist curve of $TF(s)$ gradually approaches the point $(-1,0)$, and the stability gradually weakens. When the power deficit reaches 50 kW, the Nyquist curve encircles the point $(-1,0)$, indicating that the microgrid system will lose stability. Therefore, when transitioning off-grid, the size of the power deficit in the microgrid system must be carefully considered to avoid instability caused by an excessive power deficit.

Table 1. Simulation parameters for a DC microgrid system.

Parameter	Value	Parameter	Value
DC bus voltage U_{dc}/V	750	Photovoltaic output power P_{pv}/kW	35
Photovoltaic DC-side capacitor $C_{pv}/\mu F$	500	DAB battery-side capacitor $C_1/\mu F$	1000
DC capacitor on the power grid side $C_{dc}/\mu F$	5000	DAB DC-side capacitor $C_2/\mu F$	1000
DAB voltage loop PI value	0.055	Droop coefficient k	based on the case study
DAB transformer ratio n	240/750	DAB resonant inductor $L_b/\mu H$	15
DAB switching period $T_s/\mu s$	50	Battery voltage U_c/V	240

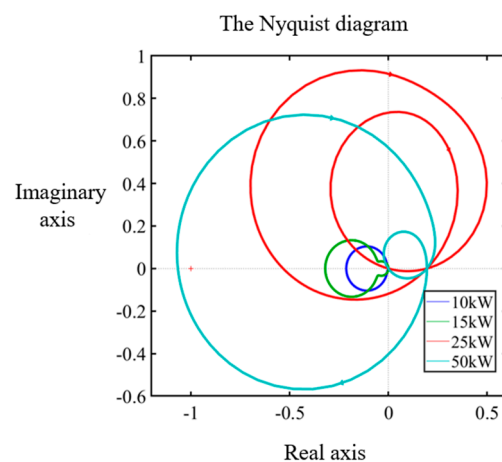


Figure 8. Nyquist plot of $TF(s)$ under different power deficits.

Additionally, to study the impact of different droop coefficients on the stability of the DAB energy storage system, a power deficit of 15 kW is set, and the stability of the DAB system is analyzed for different droop coefficients. Figure 9 shows the Nyquist plot of

$TF(s)$ under different droop coefficients k . From Figure 9, it can be observed that as the coefficient k increases, the area enclosed by the Nyquist curve of $TF(s)$ first decreases and then increases, indicating that the gain margin initially grows larger and then shrinks as k increases. When the value of k approaches 1, the Nyquist curve encircles the point $(-1,0)$, and the system becomes unstable.

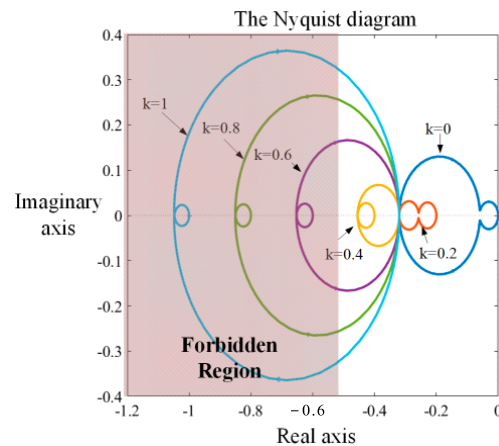


Figure 9. Nyquist plot of $TF(s)$ under different droop coefficients.

Based on the above analysis, to ensure the stability of the system in islanding operation, an appropriate droop coefficient k needs to be selected. According to Middlebrook's forbidden region stability criterion [35], when the value of k is between 0 and 0.4, the Nyquist curve stays away from the forbidden region, ensuring at least a 60° phase margin and 6 dB gain margin, indicating a certain degree of stability. On this basis, $k = 0.3$ is selected as the droop coefficient in this study.

4. Simulation Analysis and Verification

To verify the effectiveness of the theoretical analysis and parameter selection in this paper, based on the DC microgrid structure shown in Figure 1, a simulation platform is built using MATLAB/Simulink. The photovoltaic system incorporates an MPPT module, and the load is a 35 kW constant power load (CPL). System parameters are listed in Table 1. The DC/DC converter of the photovoltaic array adopts a Boost topology, with the control strategy being maximum power point tracking (MPPT) control. In the photovoltaic power station, each group contains 60 series-connected photovoltaic cells, with two such groups in series (i.e., 120 photovoltaic cells in series per branch) and 60 parallel columns. The rated output power is 35 kW, the bus voltage is 750 V, the DC load power is defined according to the case study, and the primary battery cluster of the DAB energy storage system adopts the Lithium-Ion model. The Figure 10 is the UI characteristic curve of a single photovoltaic cell's output:

The settings for case study 1 are as follows: The DC power deficits are set to 15 kW, 25 kW, and 50 kW, respectively. The droop coefficient k of the DAB energy storage system is set to 0. The system goes off-grid and enters islanding mode at 3.5 s, and the DAB energy storage system is connected to the DC microgrid to compensate for the power deficit.

Figure 11 shows the power output curve on the DC bus side of the DAB energy storage system under different off-grid power deficit conditions. Figure 12 shows the simulated waveform of the DC bus voltage corresponding to the power fluctuations.

As shown in Figures 11 and 12, with the droop coefficient $k = 0$, when the power deficit is 15 kW, the DAB energy storage system operates stably. There is a slight fluctuation in output power when the system goes off-grid, but it returns to normal after 0.15 s, and the bus voltage magnitude remains essentially unchanged. As the power deficit increases to

25 kW, the amplitude of the output power increases, the number of oscillations rises, and the recovery time extends to 0.22 s. The bus voltage magnitude decreases by 30 V compared to grid-connected operation. When the power deficit increases to 50 kW, the output power of the DAB oscillates violently, the DC bus voltage magnitude gradually drops, and the system loses stability. The simulation results confirm the correctness of the small-signal analysis theory discussed in Section 3.

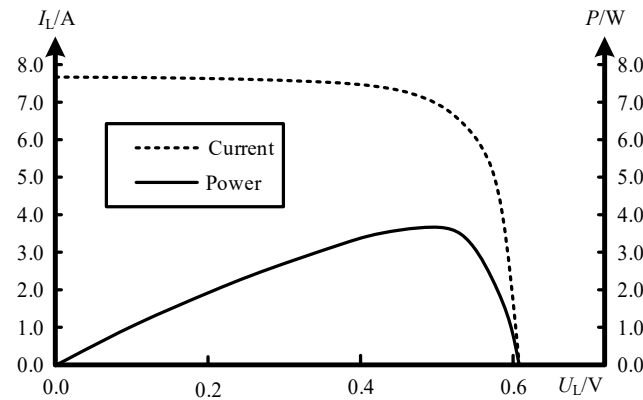


Figure 10. Voltage–current (UI) characteristic curve for the output of a single photovoltaic cell.

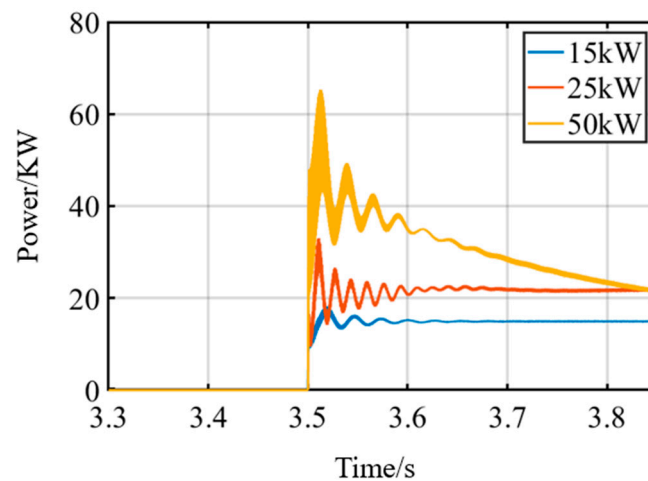


Figure 11. Power output waveform of DAB under different power deficits.

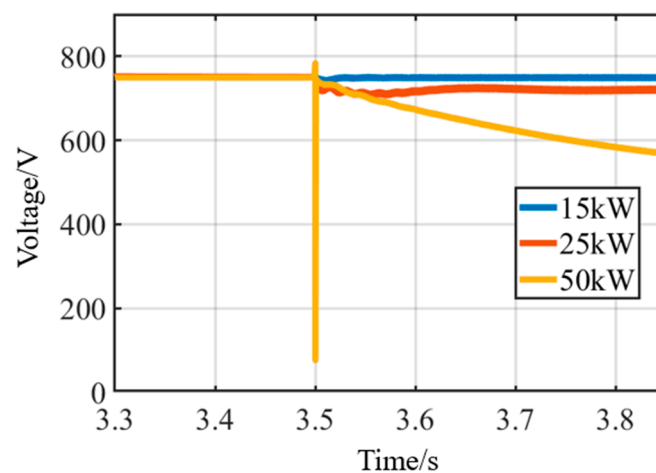


Figure 12. DC bus voltage waveform under different power deficits.

The settings for case study 2 are as follows: the DC power deficit is 15 kW; the droop coefficient k of the DAB energy storage system is set as 0, 0.2, 0.4, 0.6, and 0.8, respectively; and other parameters are the same as those in case study 1.

From Figure 13, it is important to note that when the droop coefficient $k \geq 0.8$, the grid becomes unstable, resulting in significant fluctuations in the DAB output power. The output power curves overlap and interleave within the 10 s simulation time, making visual observation difficult. Specifically, beyond $k = 0.8$, the small-signal stability of the energy storage system's power response deteriorates, leading to sustained output power oscillations.

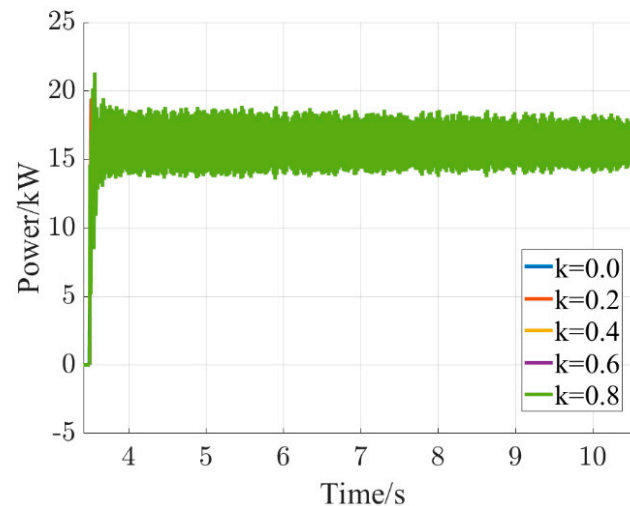


Figure 13. Power output waveform of DAB under different droop coefficients.

To facilitate analysis, the output waveforms of the DAB under different droop coefficients at the off-grid moment are specifically zoomed in on and presented for emphasis in Figure 14:

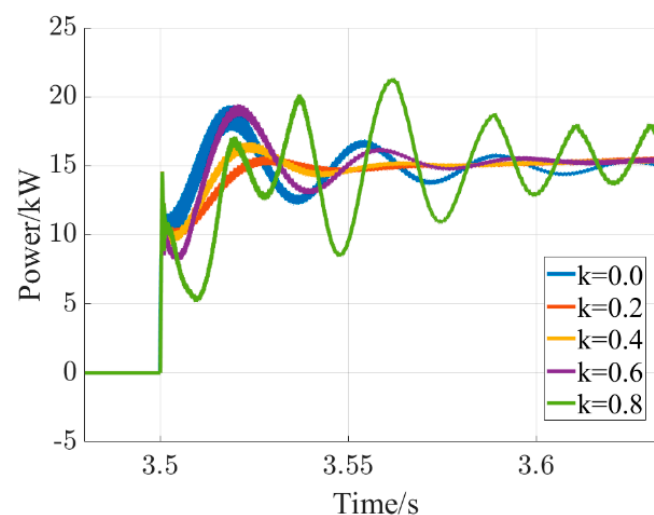


Figure 14. DAB output power waveforms under different droop coefficients at off-grid moment.

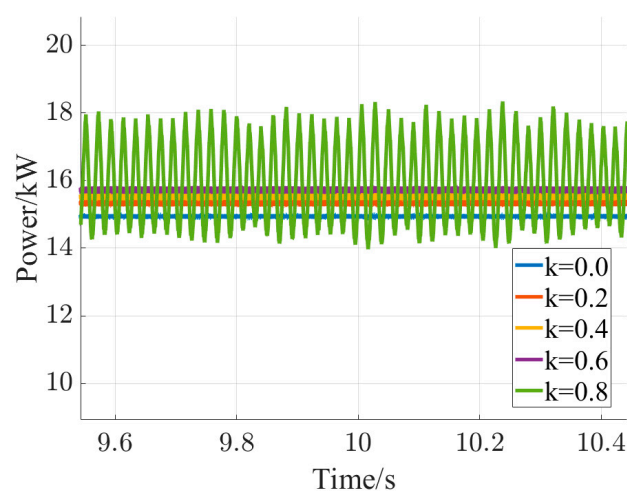
Further statistical analysis was performed on the overshoot and settling time of the power response under different droop coefficients in the figure, with the settling time defined as the time required for the response to settle within $\pm 5\%$ of the steady-state value (i.e., within the range of 14.25 kW to 15.75 kW). The statistical results are presented in Table 2.

Table 2. Statistics of settling time parameters under different droop coefficients.

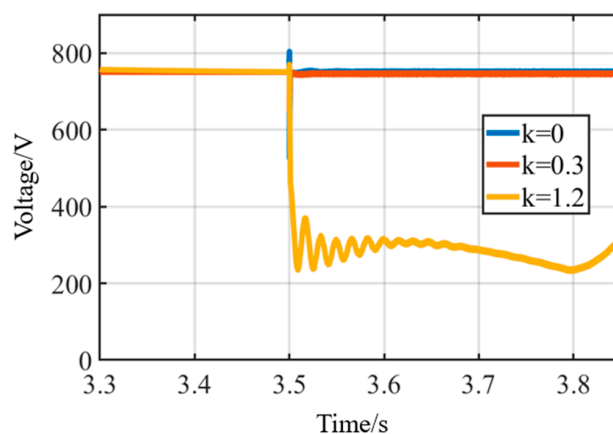
Parameter	k = 0	k = 0.2	k = 0.4	k = 0.6	k = 0.8
Overshoot/%	28.87	4.27	10.8	29.6	×
Settling Time/s	0.09	0	0.04	0.65	×

From Table 2, it can be observed that as the droop coefficient increases, both the overshoot and settling time first decrease and then increase. This trend indicates that system stability initially improves before deteriorating, which further validates the results of the small-signal analysis presented in Section 3.

Figure 15 shows DAB output power waveforms at 10 s after the off-grid transition, it can be observed that the power output increases with the droop coefficient k . The primary reason for this is that an increase in the droop coefficient leads to a reduction in the voltage at the DAB output terminal. As the voltage decreases, the power output of the photovoltaic power station decreases accordingly. To meet the constant power load demand, the DAB energy storage system must increase its power output.

**Figure 15.** DAB output power waveforms under different droop coefficients at 10 s after off-grid transition.

To clarify the relationship between droop coefficients, Figure 16 presents the power variations on the DC bus side of the DAB converter during the off-grid moment for cases with no droop control, a droop coefficient of 0.3, and a droop coefficient of 1.2. Figure 17 shows the simulation waveforms of the DC bus voltage responding to power fluctuations, while Figure 17 provides an amplified view of the voltage transient at the off-grid moment.

**Figure 16.** DC bus voltage waveform under different droop coefficients.

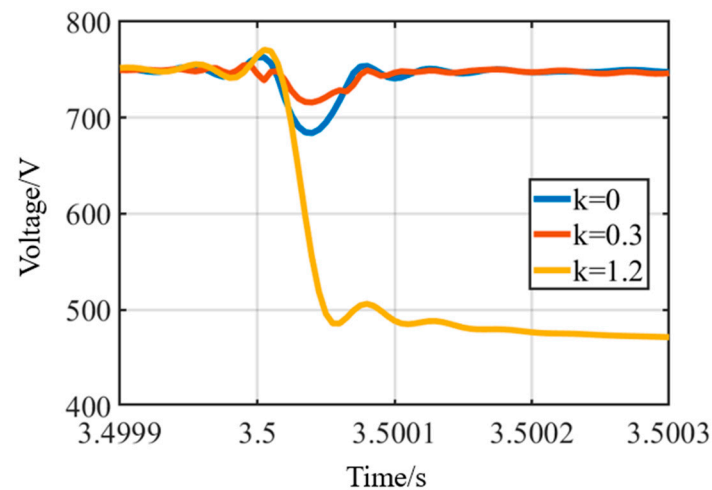


Figure 17. Amplified waveform of DC bus voltage at different droop coefficients during off-grid operation.

From Figures 14, 16 and 17, we can see that, with a power deficit of 15 kW and without using the droop control strategy, there are fluctuations in the DAB output power and an overshoot in the voltage. When the droop coefficient is set to 0.3, the power overshoot and voltage fluctuations are significantly reduced, allowing the system to reach the steady-state operating point faster. However, when the droop coefficient is set to 1.2, severe fluctuations in the output power occur, leading to a rapid drop in the bus voltage and system instability.

Compared to the case without droop control, selecting an appropriate droop coefficient allows the DAB energy storage system to effectively smooth out the power deficit during the off-grid transition, reduce power output fluctuations, and enhance the stability of the DC microgrid during islanded operation. However, as discussed in Section 4, if the droop coefficient exceeds the small-signal disturbance stability range, the power deficit cannot be smoothed, causing large fluctuations in both power and voltage on the bus, ultimately leading to system instability.

5. Conclusions

Due to the low-inertia characteristics of DC microgrids, power deficits during off-grid transitions can cause significant voltage fluctuations and stability issues. This study proposes a voltage droop-based control strategy for DAB energy storage systems to address these challenges. By constructing a small-signal model incorporating the DAB converter's dynamics and droop equation, a theoretical relationship between the droop coefficient and system stability was established. The Nyquist stability criterion confirmed that selecting an optimal droop coefficient ($k = 0.3$) improves system stability margins, ensuring at least a 60° phase margin and 6dB gain margin. The simulation results validated the proposed method: when the power deficit was 15 kW, the power response overshoot was reduced from 28.87% to 4.27%, and the settling time decreased from 0.09 s to 0 s. These improvements demonstrate the effectiveness of the droop coefficient tuning method in suppressing oscillations and enhancing dynamic performance. The strategy also maintains stable operation under higher power deficits (e.g., 25 kW), where the voltage deviation was limited to 30 V compared to grid-connected operation. However, excessive droop coefficients ($k \geq 0.8$) led to system instability, confirming the importance of proper parameter selection. Overall, this approach provides a practical solution to improve DC microgrid stability during off-grid transitions through systematic analysis and experimental validation.

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