An optimised state-of-charge balance control strategy for distributed energy storage units in islanded DC microgrid

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Abstract
The optimised droop control method is proposed to achieve the state-of-charge (SoC) balance among parallel-connected distributed energy storage units in islanded DC microgrid, which considers the difference of line impedance, initial state-of-charge values and capacities among distributed energy storage units. Since the droop control is the basic control strategy for load sharing in DC microgrid applications, however, the load sharing accuracy is degraded under conventional droop control method due to the unmatched line impedance in reality. Meanwhile, the initial state-of-charge values and capacities of each distributed energy storage unit are usually different. Hence, the state of charge for distributed energy storage units cannot be balanced. In order to prolong the lifetime of the distributed energy storage units and avoid the overuse of a certain distributed energy storage unit, the optimised droop control strategy based on sample and holder is designed, by modifying the droop coefficient adaptively, the accurate load sharing and balanced state of charge among distributed energy storage units are both obtained. Finally, the performance of the proposed control scheme is accessed through a series cases on technologies real-time digital simulator (RTDS) and its effectiveness is verified.

1 | INTRODUCTION

Over the last decade, the tremendous pressure caused by global energy crisis and environmental pollution poses a significant challenge to the sustainable development of human society [1, 2]. With the rapid growth of distributed generation technology, the renewable energy sources (RES) including photovoltaic (PV) and wind power may be widely concerned. Microgrid is introduced as an effective method to integrate those distributed generations (DGs) and loads [3–7]. It can not only realise its internal coordination and optimised operation but also provide various auxiliary services for the main utility grid. Then DC microgrid can be widely applied in data centres, telecom systems and some residential and commercial buildings [8] for its lower cost, lower transmission loss and higher reliability compared to AC microgrid, which may become the trend in recent studies [9, 10].

As an important part of the future smart grid, microgrid can operate in both islanded and grid-connected modes [9, 11, 12]. When the grid-connected interface inverter is activated, the DC microgrid will operate in grid-connected mode to exchange power with the main utility grid. Once the interface inverter is deactivated, the DC microgrid will transform to operate in islanded mode. However, it is worth mentioning that due to the intermittent and instable nature of the RES, the distributed energy storage units (DESUs) become an indispensable part to guarantee the reliable operation of DC microgrid [13–15]. To maximise the efficiency of the DESUs and avoid the overuse of DESU, proper coordination and control strategy is required to be designed in order to guarantee the proper power sharing to achieve the state-of-charge (SoC) balance among DESUs [16].

Droop control and its variants are the most commonly used method. Conventional droop control can be classified into two broad categories. One is current-mode droop which includes current–voltage ($I-V$) droop and power–voltage ($P-V$) droop. The other is voltage-mode droop which includes DC voltage–current ($V-I$) and DC voltage–power ($V-P$) droop.
When the voltage-mode droop is used in DESUs for load sharing, the SoC information of the energy storage unit is not considered in droop control. Therefore, the research on the comprehensive control method of load sharing and SoC balance is the current challenge [19, 20]. To realise the balanced SoC among DESUs in the DC microgrid, many studies have been investigated. In [21, 22], an adaptive SoC-based droop control method is presented, in which the droop coefficient is set as reciprocal of the $n$th order of SoC in charging mode, whereas in proportional to the $n$th order of SoC in charging mode, under this control scheme, the difference of the SoC among each DESUs gradually becomes smaller, and finally, the power is equally distributed, as well as ensures the SoC balance among DESUs. In [23, 24], the coordinated control strategy has been developed using the consensus algorithm to maximise the utilisation of DESUs, in which the droop coefficient is in proportional to the difference between the SoC and the average SoC value. In [25], by establishing a distributed cooperative control framework with two-layer control, the equal SoC control is realised in the secondary control through adding a voltage compensation item incorporated the SoC of each electric springs in a DC microgrid. Both aforementioned studies can well eliminate the impact of different initial SoC levers on SoC balancing control; however, when taking the inevitable line impedance into consideration, the power sharing accuracy may be degraded and conventional droop control can cause each DESU to operate at a different charging or discharging power/current. As a result, the SoC levels of the DESUs ultimately diverge.

For the purpose of optimising the load sharing issue and reaching SoC equilibrium, a lot of studies have also been conducted. In [16], the concept of virtual power rating is introduced, and the impact of line impedance is eliminated through the proportional integral controller. At the same time, the SoC adjustment compensation item is added to the control system as voltage compensation. A multi-agent sliding mode control based on linear consensus protocols to eliminate the influence of the unmatched line impedance and realise rapid SoC balancing among DESUs in the DC microgrid is presented [26], but the performance will be degraded when the transient output power error between the DESUs is large, and the phenomenon of over-charging or over-discharging still cannot be avoid. In addition, a double-layer hierarchical control strategy is proposed in [27] to achieve SoC balancing control between DC microgrid DESUs. However, the application of central controller may result in a single point of failure, and the communication and processing infrastructure for centralised SoC estimation and control may be impractical for microgrid with many small DESUs. Meanwhile, data centralisation may introduce privacy and security concerns. In [28], the distributed coordinated control strategy including load distribution and energy storage balance is proposed. The control objective is achieved by transmitting various information data between adjacent units, but the drawback is amount of data needs to be acquired.

Based on the above analysis, an optimised droop control strategy for accurate load (power/current) sharing as well as achieving the SoC balance among DESUs in DC microgrid is proposed. The control method is easy to implement, by introducing the sample and holder (S/H), without knowing the specific parameter value of line impedance, as long as there is load sharing deviation and the SoC imbalance in the DC microgrid, the droop coefficients are adaptively adjusted at every sampling period until both load sharing and SoC deviations of each DESU are removed.

The rest of paper is organised as follows. Section 2 depicts the typical configuration of the microgrid and the inherent limitations of load sharing error under conventional voltage-mode droop control methods are expounded, and then the affection factors of the SoC equilibrium can be analysed. In Section 3, the proposed droop control strategy is elaborated. Meanwhile, the specific theoretical argumentation analysis about the optimised $V-P$ droop control is discussed. To verify the effectiveness of the proposed droop control strategy, the examined case studies based on the real-time digital simulator (RTDS) platform have been carried out and the illustrative results are presented in Section 4. Finally, Section 5 makes a conclusion of this work.

2 CONFIGURATION OF MICROGRID AND ANALYSIS FOR SoC BALANCING

2.1 Configuration of typical microgrid

Figure 1 presents the typical configuration of the microgrid, which consists of a number of RES (e.g., PV), DESUs, main utility grid and loads which are connected in parallel to the common DC bus through appropriate power electronics converters and line impedances, respectively. When the grid-interfacing converter is disconnected, the DC microgrid will operate in islanded mode. Since the PV usually operates in maximum power point tracking mode to take full advantage of RES, therefore, the DESUs are responsible for regulating the DC bus voltage and mitigating the power fluctuations caused by PV generation and load fluctuation via charging and discharging processes.
In such a condition, if the PV generation releases more power than load consumption, thus, the DESUs will operate in charging mode to absorb the redundant power. Conversely, if power generated by PV generation cannot meet the load demand requirement, the DESUs will be allowed to work in discharging mode to support the power balance of the whole DC microgrid.

2.2 Conventional voltage-mode droop control and its influence on SoC

The conventional voltage-mode droop control methods, which including \( V \sim P \) droop control and \( V \sim I \) droop control, have been widely adopted for autonomous load sharing issue among DESUs in DC microgrid, and its expression is given in (1). The output power/current can easily change by adjusting the droop coefficient, when the droop coefficient increases, the output power/current is reduced accordingly, and the output power/current increases for the opposite situation:

\[
V_{D_{\text{i}}} = V_{\text{nom}} - k_{i} \lambda_{i}, \tag{1}
\]

where \( V_{D_{\text{i}}} \) represents the output voltage of \( i \)th DESU, \( V_{\text{nom}} \) represents the nominal voltage of the DC microgrid at no load condition, \( k_{i} \) represents the droop coefficient of \( i \)th DESU and \( \lambda_{i} \) represents the output power/current of \( i \)th DESU. \( \lambda_{i} \) is positive when discharging, and negative when charging.

During the operation of the DESUs, the SoC, as an important indicator for measuring the available capacity of the DESUs, since the DESUs consist of a series of DESUs with different initial SoC levels and capacities, as well as the accordingly converters are connected to the common DC bus through different line impedances. To avoid the overuse of a certain DESU and prolong the lifetime of the DESUs, SoC balancing control is developed to guarantee the contributions of DESUs to keep accordance. This means that the DESU with higher SoC lever should release more power/current in discharging mode while absorbing less power/current in charging mode, and the DESU of lower SoC level should release less power/current in discharging mode while absorbing more power/current in charging mode. The most commonly used estimation method of SoC is the coulomb counting method shown as follows [20]:

\[
\text{SoC}_i(t) = \text{SoC}_i(0) - \int \frac{I_{i}}{C_{i}} dt = \text{SoC}_i(0) - \int \frac{I_{V_{D_{\text{i}}}}}{C_{i}V_{\text{in}}} dt \approx \text{SoC}_i(0) - \int \frac{I_{i}}{C_{i}V_{\text{in}}} dt, \tag{2}
\]

where \( \text{SoC}_i(0) \), \( I_{i} \) and \( P_{i} \) are the initial value of \( i \)th DESU, the output current and the output power of \( i \)th DESU, respectively. \( C_{i} \) is the capacity \( i \)th DESU, \( V_{\text{in}} \) and \( I_{\text{in}} \) are the output voltage and the output current of \( i \)th battery, respectively. \( I_{i} \), \( I_{\text{in}} \) and \( P_{i} \) are positive in the discharging process, and negative in the charging process.

Deriving both sides of Equation (2) and combining Equation (1), it yields:

\[
\frac{d\text{SoC}_i}{dt} = - \frac{I_{i}(V_{\text{nom}} - k_{i} I_{i})}{C_{i}V_{\text{in}}} = - \frac{P_{i}}{C_{i}V_{\text{in}}} \tag{3}
\]

\[
\text{SoC}_{\text{min}} \leq \text{SoC}_i \leq \text{SoC}_{\text{max}}, \tag{4}
\]

where \( \text{SoC}_{\text{min}} \) and \( \text{SoC}_{\text{max}} \) denote the minimum and maximum limits of SoC, respectively.

From Equation (3), it can be summarised that the charging and discharging rates of SoC of the \( i \)th DESU are determined by the output power/current and the capacity of individual DESU.

Meanwhile, in reality, the external circuit also has an impact on the load sharing accuracy, and the performance of ideal load sharing under conventional droop control method is destroyed due to the unmatched line impedance between DESUs. To elaborate the load sharing issue, an equivalent DESUs model is built as shown in Figure 2, in which \( R_{\text{line}i} \) and \( R_{\text{line}j} \) are the equivalent line impedance of DESU \( i \) and DESU \( j \), respectively, \( V_{\text{pcc}} \) is the DC bus voltage and \( P_{\text{load}} \) is the load power on common DC bus.

From Figure 2, the common DC bus voltage can be calculated as follows:

\[
V_{\text{pcc}} = V_{D_{\text{i}}} - I_{i}R_{\text{line}i} = V_{D_{\text{j}}} - \frac{P_{j}}{V_{D_{\text{j}}}}R_{\text{line}j}. \tag{5}
\]

Substituting (1)–(5), the load distribution (output current and output power) ratio of DESUs can be written as follows:

\[
\frac{I_{i}}{I_{j}} = \frac{k_{j} + R_{\text{line}i}}{k_{i} + R_{\text{line}j}}, \tag{6}
\]

\[
\frac{P_{i}}{P_{j}} = \frac{k_{j} + \frac{R_{\text{line}i}}{V_{D_{\text{j}}}}}{k_{i} + \frac{R_{\text{line}j}}{V_{D_{\text{j}}}}}. \tag{7}
\]

From (6) and (7), it can be clearly observed that the accurate load distribution among DESUs is not only related to the droop coefficients but also related to the line impedances. However, in reality, the existence of unmatched line impedance cannot be ignored, thus, the conventional droop control method always leads to load distribution errors. Consequently, it is
impossible for the DESUs to achieve the SoC equilibrium control.

3 Optimised SoC Balancing Control Strategy

3.1 Design of Optimised SoC Balancing Control

As previously analysed, the DESUs SoC balancing control is related to the SoC levels, capacities and the output power or output current which greatly influenced by unmatched line impedance. For the purpose of obtain balanced SoC control between DESUs, this paper designs an optimised droop control scheme, in which the droop coefficient is automatically changed with the SoC levels and the output power/current states until the balanced SoC is realised.

\[ V_{D-i(n+1)} = V_{\text{nom}} - k_i V_i \]  

(8)

\[ K_i = k_0 + k_{\lambda} + k_{\alpha} \]  

(9)

\[ K_{\lambda} = k_{\lambda} (\gamma_i - \gamma_{\text{ave}}) \]  

(10)

\[ \gamma_i = \frac{\lambda_i}{C_i}, \gamma_{\text{ave}} = \frac{1}{N} \sum_{i=1}^{N} \lambda_i \]  

(11)

\[ K_{\alpha} = k_{\alpha} (S_{i\text{ave}} - S_{\text{ave}}) \]  

(12)

\[ S_{\text{ave}} = \frac{1}{N} \sum_{i=1}^{N} S_{i} \]  

(13)

where \( V_{D-i(n+1)} \) is the output voltage of \( i \)th DESU in the \( n \)th sampling period; \( K_i \) is the droop coefficient of \( i \)th DESU in the \( n \)th sampling period; \( k_0 \) is the initial droop coefficient; \( K_{\lambda} \) is the change of the droop coefficient used for eliminating the load sharing errors in the \( n \)th sampling period; \( k_{\lambda} \) is the load adjustment factor; \( \lambda_i \) and \( \lambda_{\text{ave}} \) are the output power/current and average output power/current of \( i \)th DESU in the \( n \)th sampling period, respectively; \( K_{\alpha} \) is the change of the droop coefficient used for narrowing the difference between SoC in the \( n \)th sampling period; \( k_{\alpha} \) is the SoC adjustment factor; \( S_{\text{ave}} \) is the SoC and average SoC of \( i \)th DESU in the \( n \)th sampling period, respectively.

Figure 3 illustrates the total control structure of the proposed droop control strategy for DESUs in islanded DC microgrid, where \( S/H \) is the sample and holder, \( S \) is the synchronisation signal; \( S = 1 \) indicates that \( S/H \) is working and the DESU is operating in the optimised droop control method, while \( S = 0 \) means that \( S/H \) is not activated and the DESU is operating in the conventional droop control.

The specific working process can be summarised as the local \( S/H \) controller in each DESU, which sample the information of output power/current and SoC, and transmit them to the central controller. According to (11) and (13), \( \gamma_{\text{ave}} \) and \( S_{\text{ave}} \) are calculated. If there exist power/current error or the SoC unbalanced, the DESU operates in the optimised droop control method and the local controller adjusts its droop coefficient on the basis of (9), (10) and (12) adaptively. The droop coefficient will not change until the power/current error is removed and the SoC is balanced.

3.2 Analysis of Optimised SoC Balancing Control

In order to further elaborate the detail mechanism of the proposed droop control to achieve SoC balancing control strategy, take two DESUs (DESU1, DESU2) with the same capacity, for example. The proposed droop control method (8) can now be applied to \( V_{\text{nom}} \) droop control expressed in (14):

\[ V_{D-i(n+1)} = V_{\text{nom}} - K_i (P_i - P_{\text{ave}}) \]  

(14)

\[ K_i = k_0 + k_{\lambda} (P_i - P_{\text{ave}}) + k_{\alpha} (S_{\text{ave}} - S_{\text{ave}}) \]  

It is assumed that the two DESUs have the same capacity and initial SoC. Once the synchronisation signal \( S = 1 \), the proposed \( V-P \) droop control begins to work. After the first sampling period, (14) can be written as follows:

\[ V_{D-i(1)} = V_{\text{nom}} - [k_0 + k_{\lambda} (P_i - P_{\text{ave}})] P_i \]  

(15)
At the same time, the error of SoC between DESUs can also be derived as follows:

\[ \Delta \text{SoC}_{i-j,(n+1)} = \text{SoC}_{i-j,(n)} - \frac{1}{C_i V_{in}} \int (P_{i,(n)} - P_{j,(n)}) dt \]

\[ = \text{SoC}_{i-j,(n)} - \frac{T_{\text{sample}}}{C_i V_{in}} (P_{(n)} - P_{j,(n)}) \] (16)

where \( T_{\text{sample}} \) is the sampling period of \( S/H \).

If the DESUs are in discharging mode, and \( R_{\text{line}i} > R_{\text{line}j} \), the output power satisfies initial relation \( 0 < P_{i,(0)} < P_{j,(0)} \), in the first sampling period, according to Equation (3), \( \text{SoC}_{i,(0)} > \text{SoC}_{j,(0)} \). Then, it can be obtained that \( k_i (P_{(0)} - P_{\text{ave}(0)}) < 0 < k_j (P_{(0)} - P_{\text{ave}(0)}) \). At the same time, with the different \( \text{SoC}_{i,(0)} \), \( k_i (\text{SoC}_{i,(0)} - \text{SoC}_{\text{ave}(0)}) < 0 < k_j (\text{SoC}_{j,(0)} - \text{SoC}_{\text{ave}(0)}) \). As shown in Figure 4, \( k_i \) represents the initial droop coefficient, and the droop coefficient satisfies \( K_i(1) < k_i < K_j(1) \) after the first sampling period, which means that DESU\(_i\) should decrease its droop coefficient while DESU\(_j\) should increase its droop coefficient. The power sharing of DESUs after the first sampling period is shown in Figure 4.

Figure 4 shows that \( P_{i,(0)} < P_{i,(1)} < P_{j,(0)} \), the power sharing error between DESUs decreases. When the sampling period continues, the local controller adjusts the droop coefficient adaptively until the power error completely eliminated. Therefore, it can be clearly observed from (16) that the absolute error of SoC between DESUs also reduces constantly. Finally, the SoC balancing control is realised.

If the DESUs are in charging mode, the power sharing diagram after the first sampling period is shown in Figure 5. The output power satisfies \( P_{i,(0)} < P_{i,(1)} < P_{j,(0)} < 0 \), and the SoC meets \( \text{SoC}_{i,(1)} < \text{SoC}_{j,(1)} \), therefore, \( k_i (P_{(0)} - P_{\text{ave}(0)}) < 0 < k_j (P_{(0)} - P_{\text{ave}(0)}) \), \( k_i (\text{SoC}_{i,(1)} - \text{SoC}_{\text{ave}(1)}) < 0 < k_j (\text{SoC}_{j,(1)} - \text{SoC}_{\text{ave}(1)}) \), thus, the droop coefficient satisfies \( K_i(1) < k_i < K_j(1) \) with the sampling period continues, which means that DESU\(_i\) should decrease its droop coefficient, while DESU\(_j\) should increase its droop coefficient. Similar to the discharging mode, the power sharing error between DESUs decreases, and the absolute error of SoC between DESUs also reduces constantly. Finally, the SoC balancing control is realised.

The working principle of SoC balancing control during charging or discharging condition of DUSUs with different initial SoC is similar to the aforementioned analysis. It is concluded that no matter how the line impedance changes and regardless of the initial SoC level, once the SoC is unbalanced, the DESUs can automatically adjust the droop coefficient based on their output power and SoC level until the SoC equilibrium control is reached.

### TABLE 1 System parameter

| Parameter                      | Symbol | Value            |
|-------------------------------|--------|------------------|
| Nominal voltage at no load    | \( V_{\text{nom}} \) | 400 V            |
| Line impedance of DESU\(_i\) | \( R_{\text{line}i} \) | 0.1 \( \Omega \) |
| Line impedance of DESU\(_j\) | \( R_{\text{line}j} \) | 0.2 \( \Omega \) |
| Line impedance of DESU\(_k\) | \( R_{\text{line}k} \) | 0.3 \( \Omega \) |
| Voltage variation             | \( \Delta V \) | \( \pm 5\% V_{\text{nom}} \) |
| Initial droop coefficient     | \( k_0 \) | \( 1 \times 10^{-5} \) |
| Load adjustment factor        | \( k_i \) | \( 5 \times 10^{-3} \) |
| SoC adjustment factor         | \( k_j \) | \( 8 \times 10^{-5} \) |
| Capacity of DUSUs             | \( V_i \) | 12               |
| Sampling period               | \( T_{\text{sample}} \) | \( 1 \times 10^{-4} \) s |

### 4 RTDS SIMULATION RESULTS

In order to verify the effectiveness of the proposed SoC balancing control strategy, experimental study based on RTDS platform is carried out. The islanded DC microgrid model which consists of three parallel-connected DESUs (DESU\(_1\), DESU\(_2\), and DESU\(_3\)) is depicted in Figure 6. The main parameters of the DC microgrid are listed in Table 1.

The proposed SoC balancing control strategy is applied to the following four operational scenarios (case 1, case 2, case 3 and case 4):
case 4). Case 1 is designed to verify that the DESUs can reach ideal SoC balancing control performance both in stable charging or discharging conditions. In case 2, the PV generation fluctuates, and the DESUs will change their operating state accordingly; case 2 is employed to validate whether SoC balancing control will be affected during this period. Case 3 aims to testify the SoC balancing control performance while the load fluctuates dynamically. Gradual disturbance is introduced in case 4, and the robustness of the proposed control strategy is verified successfully.

4.1 Case 1: Stable charging or discharging conditions for DESUs

In this case, the performance of the proposed SoC balance controls strategy in the conditions that the DESUs in stable charging and discharging are testified. To elaborate the proposed control strategy more detail, $V-P$ droop control is adapted (cases 2–4 are same). In islanded DC microgrid, the DESUs are necessary to keep the balance between PV generation and load power consumption in real time. When the PV generation cannot meet the load power demand, the DESUs is in stable discharging condition to satisfy the load power requirement, and while the PV generation still has surplus after meeting the load power consumption, consequently, the DESUs operate in stable charging condition to absorb extra power.

Figure 7 illustrates the RTDS results of DESUs in stable discharging process. The initial SoC of DESUs are all set as 80%, and in the first 4 s, the DESUs operate in the conventional droop control; 4 s later, the proposed droop control begins to work. As shown in Figure 7(a) and (b), because of the unmatched line impedance, the SoC and output power of DESUs cannot be shared accurately. Therefore, the SoC of DESUs appears as an uneven phenomenon and its errors get bigger during $0 \sim 4$ s. At the time $t = 4$ s, the SoC of DESUs starts to converge and the DESU with higher SoC is observed to release more power while the lower SoC releases less power. Finally, both output power and SoC gradually become similar. It indicates that the proposed SoC balancing control solution can well eliminate the impacts of unmatched line impedance and characteristics difference among DESUs. In addition, Figure 7(c) presents that, under the proposed control strategy, the DC bus voltage of DC microgrid still be maintained within allowable region.

Figure 8 is the RTDS result of DESUs in a stable charging condition. The initial SoC of DESUs are assumed as 50%, in the period of $0 \sim 4$ s, the DESUs operate in the conventional droop control and begin to work in the proposed droop control at $t = 4$ s. As shown in Figure 8(a) and (b), once the DESUs...
are switched to the proposed droop control method, the SoC and output power gradually converge. It is observed that the DESU with lower SoC absorbs less power, while the higher SoC absorbs more power until the SoC of DESUs is balanced. Thus, the droop coefficient no longer changes. Figure 8(c) shows that the proposed SoC balancing control strategy has no effect on the stable operation of the bus voltage, and the voltage deviation generated by the droop control is always limited within the acceptable range.

4.2 Case 2: Performance of DESUs under PV generation fluctuations

In this case, the SoC balancing control performance of DESUs against PV generation fluctuations is verified. The RTDS results are depicted in Figure 9.

At $t = 0$∼8 s, the DESUs are operated in discharging mode to support the stable operation of the DC microgrid. As shown in Figure 9(b), the DESUs firstly work in the conventional droop control method and there exits SoC unbalanced phenomenon caused by unmatched line impedance. At $t = 4$ s, the proposed droop control method activates and the SoC deviation between
FIGURE 10 Real-time digital simulator (RTDS) results of state-of-charge (SoC) balancing control with load fluctuation: (a) power distribution in DC microgrid, (b) SoC of distributed energy storage units (DESUs), (c) output power of DESUs and (d) DC bus voltage

DESUs are decreasing. At $t = 8$ s, from Figure 9(a), it can be seen that the PV generation abruptly increases its output power, and after meeting the load power demand, there is still power remaining in the DC microgrid, so, the DESUs quickly switch to the charging mode to absorb excess power. It can be observed from Figure 9(b) that the performance of the SoC balancing control is not affected by PV generation fluctuation. Meanwhile, the DC bus voltage shown in Figure 9(c) indicates that the proposed control strategy is also useful to stabilise DC bus voltage under PV generation fluctuation.

4.3 Case 3: Performance of DESUs under load fluctuations

In this case, the performance for DESUs SoC balancing control strategy under the condition of load fluctuation is assessed. The change of power distribution in DC microgrid and the RTDSs results are shown in Figure 10.

It is seen from Figure 10(b) that the DESUs firstly work in charging mode and the SoC gradually converges with the optimised droop control after $t = 4$ s. At $t = 8$ s, the Figure 10(a) shows that, due to which the power generated by the PV generation is less than the load power consumption, a fluctuation occurs in the load side. Thus, the DESUs are quickly switched to discharging mode to release power and maintain the power balance of the whole DC microgrid. The RTDS results shown in Figure 10(b) clearly confirms that the performance of DESUs SoC balancing control is not affected by load fluctuation, and can still achieve a perfect balance control effect. Figure 10(d) demonstrates that the DC bus voltage can also be maintained within an allowable region.

4.4 Case 4: Performance of DESUs under gradual disturbance

In this case, the performance of the proposed SoC balance control strategy under the condition of gradual disturbance is studied. The change of power distribution and the RTDSs results is shown in Figure 11.

Figure 11 is the RTDS result of DESUs in charging condition. The control strategy is switched after $t = 4$ s. It can be seen from Figure 11(b) and (c) that the influence of line impedance is successfully eliminated, SoC balancing is achieved and DESUs distribute load power in accordance with the rated ratio. As seen from Figure 11(a), a gradual disturbance appears at $t = 8$ s. The gradual disturbance here simulates the output fluctuation of the intermittent distributed generations in the actual operation. The results in Figure 11 reflect that the gradual disturbance has no effect on the system, the SoC imbalance and the output power sharing deviation is eliminated. Figure 11(d) reflects that the bus voltage fluctuates with disturbance, but the voltage level is still within the allowable range, and the entire microgrid system can maintain normal operation.

5 CONCLUSION

An optimised droop control method is proposed intended to reach accurate load sharing as well as realise SoC balance control for DESUs in an islanded DC microgrid, in which the unmatched line impedance, initial SoC levels and capacity of
different DESU are all taken into account. By introducing the sample and holder, the droop coefficient can automatically be adjusted according to the load sharing error and SoC error at each sampling period. Therefore, the load (current or power) is reasonably distributed as to achieve the balanced SoC among DESUs. Finally, different cases of the proposed droop control method have been assessed on the RTDS platform, and the results validate the correctness and effectiveness of the designed control strategy in terms of achieving balanced SoC among DESUs in an islanded DC microgrid.

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