Battery State of Charge Balancing with Accurate Power Sharing in DC Microgrid

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***Abstract*— This paper proposes a distributed control method to achieve state of charge (SoC) balancing among the distributed battery energy units (BEUs) in a DC microgrid based on accurate power sharing. The distributed control algorithm estimates the average SoC of all BEUs by means of consensus algorithm, and voltage regulation is determined by comparing the per unit power of BEU with the those of the neighbors. At the same time, the estimated average SoC and the voltage regulation are used to implement accurate power sharing according to the SoC levels of BEUs to achieve the SoC balancing regardless of the line resistance difference. Moreover, the control algorithm also restores the DC voltage level to the nominal value for stable operation. The effectiveness of the proposed method is proved by simulation.**

***Index Terms*—DC microgrid, droop control, state of charge, consensus algorithm.**

I. Introduction

The the integration of DC renewable energy sources (RESs) and modern DC loads [e.g., photovoltaics (PVs), fuel cells and LEDs, etc.,] motivates the development of DC microgrid. Compared with the AC microgrid, the DC microgrid has been received more attention due to its higher efficiency for absence of intermediate AC power conversion stages, and it avoids the problems related to reactive power, harmonics and synchronization [1]–[3]. In DC microgrid, in order to guarantee the reliable operation, battery energy units (BEUs) are usually used to mitigate the power fluctuation caused by RESs such as wind power and PVs. Because BEUs are commonly distributed in microgrid system, their charging or discharging powers are different because of different line resistance [4]. As a result, their state of charge (SoC) levels become unbalanced, which can lead to over-charge or over-discharge of a certain BEU.

In order to solve this problem, a centralized control strategy was presented to provide SoC balancing among BEUs [5]. Nevertheless, the central controller may suffer from the risk of the single point failure, and it requires high computational burden which is not appropriate for the microgrid with many distributed BEUs [6]. In [7], [8], a droop scheme was proposed without using additional communication network, and the droop coefficient was modified to be inversely proportional to the exponential function of SoC (SoC^n), where 'n' is identified as the convergence factor. However, it needs stability analysis and computing complicate exponential inequalities to select the suitable convergence factor.

In the previous studies, it is hard to achieve the accurate power sharing with the balanced SoC among BEUs due to the line resistance difference, which is inevitable in the distributed DC microgrid [9]. To solve the problem, a decentralized control strategy with virtual power rating concept was proposed to realize balanced SoC with accurate power sharing in DC microgrid [10]. Nonetheless, this control strategy requires a certain BEU to share its information with all other BEUs in the microgrid through full communication network, which raises the limitation to implement and the scalability in case of large number of BEUs [11].

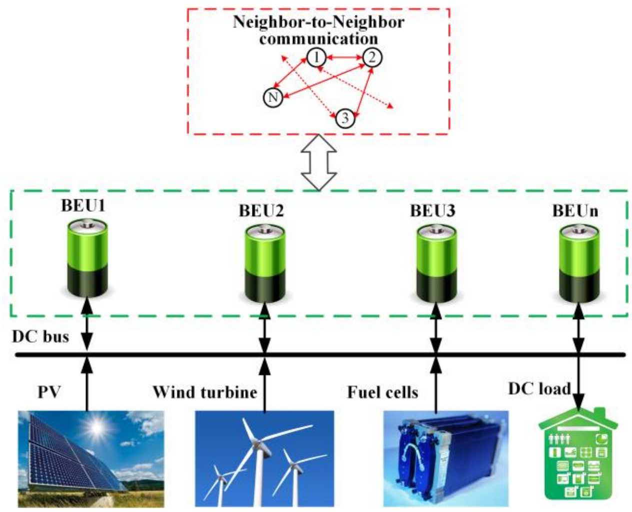

Fig. 1. DC microgrid

In this paper, we propose a consensus-based distributed control to achieve SoC balancing among BEUs with the accurate power sharing in DC microgrid. In the proposed control method, the consensus algorithm is used to utilize the distributed secondary control at local controller of each BEU in order to estimate the average SoC of BEUs and the per unit output power comparation with those of the neighbors via neighbor-to-neighbor communication network. The estimated average SoC and the per unit power comparation are further used to regulate accurate power sharing according to SoC levels among BEUs to achieve the accurate SoC balancing regardless of the line resistance difference. Moreover, the voltage restoration is also considered to guarantee the suitable voltage level of the microgrid. The proposed method is analyzed theoretically, and its effectiveness is verified by simulation.

II. Consensus Algorithm

In Fig. 1, DC microgrid contains N distributed BEUs, and

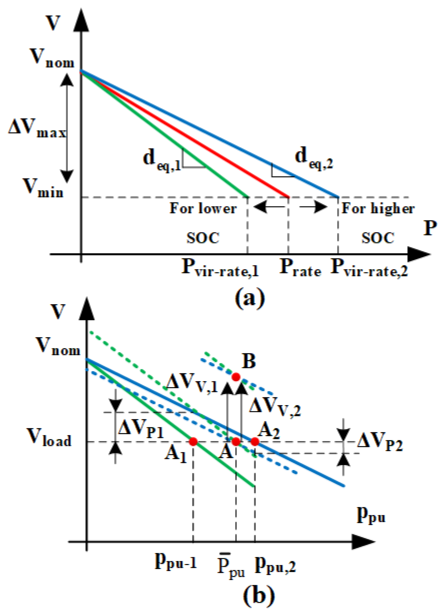

Fig. 2. Droop lines: (a) For SoC balancing, (b) For accurate power sharing and voltage restoration

each BEU is assigned as a node. The basic consensus algorithm in discrete-time form is described in [12]:

$$x_i\left(k+1\right)=x_i\left(0\right)+\varepsilon\sum_{j\in N_i}\delta_{ij}\left(k+1\right) \tag{1}$$

$$\delta_{ij}\left(k+1\right)=\delta_{ij}\left(k\right)+a_{ij}\left(x_j\left(k\right)-x_i\left(k\right)\right)\ , \tag{2}$$

where $x_i(k)$ is a state variable of the *i-th* node at the time k, a_{ij} indicates the connection status between node i and node j, a_{ij} = 0 if the two nodes are not linked, N_i is the set of nodes that can be connected with node i, δ_{ij} stores the cumulative difference between two nodes, and ε is the constant edge weight.
By applying the consensus algorithm, the state variables x of BEUs can be equalized at the same value after several iteration, and the communication between the direct neighboring BEUs is required in this process.

III. Consensus control for BEU

A. SoC Estimation Method

For power sharing among BEUs, the SoC is generally estimated by the Coulomb counting method in the following equation [7]:

$$SoC_i=SoC_i\left(0\right)-\frac{\int i_{b,i}dt}{C_{b,i}}, \tag{3}$$

where $SoC_i\,(0)$, $C_{b,i}$ and $i_{b,i}$ are the initial value of SoC, the capacity, and the output current of the *i-th* BEU, respectively.

With the assumption that the power loss in converters is negligible and the BEU voltage is constant, (3) is transformed as follows:

$$SoC_i=SoC_i\left(0\right)-\frac{\int V_{b,i}i_{b,i}dt}{V_{b,i}C_{b,i}}=SoC_i\left(0\right)-\frac{\int P_i dt}{V_{b,i}C_{b,i}}\ , \tag{4}$$

where $V_{b,i}$ and P_i are the BEU voltage and output power of the *i-th* battery, respectively. P_i is positive when discharging, and negative when charging. From (4), SoC can be balanced by regulating the output power of BEU.

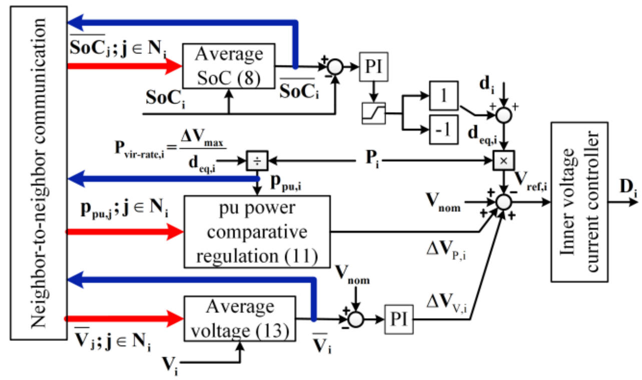

Fig. 3. Proposed control scheme

B. Consensus Control for BEU

The conventional droop control in the DC microgrid is given as follows:

$$\begin{aligned}V_{ref,i}&=V_{nom}-d_iP_i\\ d_i&=\frac{\Delta V_{\max}}{P_{rate,i}}\end{aligned}\quad , \tag{5}$$

where V_{nom} is the nominal voltage of DC microgrid, ΔV_{max} is the maximum allowable bus voltage variation, $V_{ref,i}$, d_i, $P_{rate,i}$ are the reference output voltage, droop coefficient and power rating of the *i-th* BEU, respectively.

In order to control the power sharing to achieve the SoC balancing, droop coefficient in (5) is modified as below:

$$\begin{aligned}V_{ref,i}&=V_{nom}-\left(d_i+\Delta d_i\right)P_i=V_{nom}-d_{eq,i}P_i, \quad discharge\\ V_{ref,i}&=V_{nom}-\left(d_i-\Delta d_i\right)P_i=V_{nom}-d_{eq,i}P_i, \quad charge\end{aligned} \tag{6}$$

where Δd, $d_{eq,i}$ are adjusted droop coefficient, equivalent droop coefficient of *i-th* BEU, respectively; Δd is calculated from the SoC of the BEU:

$$\Delta d_i=G_{PI,SoC}\left(\overline{SoC_i}-SoC_i\right) \tag{7}$$

In (7), $G_{PI,SoC}$ is the transfer function of the PI controller for the SoC balancing, and $\overline{SoC_i}$ is the estimated average *SoC* which is achieved at the local controller of the *i-th* BEU. By replacing $\overline{SoC_i}$ as a state variable into (1) and (2), average SoC can be estimated, and all BEUs have the same estimated average value via the consensus algorithm in (1) and (2):

$$\begin{aligned}&\overline{SoC_i}(k+1)=SoC_i(k)+\varepsilon\sum\delta_{ij}(k+1)\\ &\delta_{ij}(k+1)=\delta_{ij}(k)+a_{ij}\left(\overline{SoC}_j(\mathrm{k})-\overline{SoC}_i(\mathrm{k})\right)\end{aligned}\ . \tag{8}$$

Fig. 2(a) shows the principle of the SoC balancing method in (6) and (7). In Fig. 2(a), during discharging period, the equivalent droop coefficient $d_{eq,i}$ decreases in the case the BEU's SoC is higher than the estimated average SoC, while the equivalent droop coefficient increases for the BEU with lower SoC. Therefore, the higher SoC BEU discharges more power, and the lower SoC BEU supplies less power to the microgrid. Similarly, charging case can be explained.

However, the performance of the SoC balancing method in (6) and (7) is degraded due to the inaccurate power sharing because the droop control in (6) does not consider the effect of the line resistance [10]. In order to achieve accurate power sharing as well as SoC balancing, we propose a control method by combining the consensus algorithm with the virtual power

TABLE I
SYSTEM PARAMETERS

Parameter	Value
Nominal voltage	100V
Voltage variation	±5% (5V)
BEU power rating	500W
BEU capacity	0.1Ah
Communication delay	50ms
Initial SoC	70%, 60%, 50%, 40%

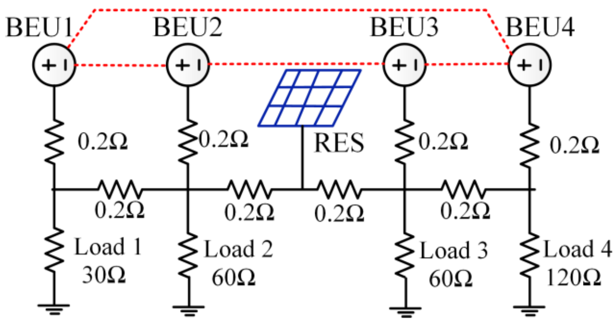

Fig. 4. DC microgrid in simulation

rating concept in [10]. The virtual power rating ($P_{vir\text{-}rate,i}$) shown in Fig. 2(a) is defined based on the maximum allowable variation and the equivalent droop coefficient:

$$P_{vir-rate,i} = \frac{\Delta V_{\max}}{d_{eq,i}} \tag{9}$$

The per unit power $p_{pu,i}$ of BEU is calculated from the virtual power rating:

$$p_{pu,i} = \frac{P_i}{P_{vir-rate,i}} \tag{10}$$

From (1) and (2), the compensating term of each BEU to share the accurate power is calculated using the per unit power comparative regulation:

$$\Delta V_{P,i} = G_{PI,P} \sum_{j \in N_i} a_{ij} \left(p_{pu,j} - p_{pu,i} \right) , \tag{11}$$

where $\Delta V_{P,i}$ is the voltage regulation for accurate power sharing of the *i-th* BEU, $G_{PI,P}$ is the transfer function of the PI controller for power sharing.

If per unit powers of any two neighbor BEUs are different, the corresponding accurate power sharing controllers respond and adjust their voltage regulation term ($\Delta V_{P,i}$) to achieve the balanced power, i.e., $p_{pu,i} = p_{pu,j}$.

In practical applications, the voltage level in DC microgrid should be maintained within the suitable region. For this purpose, a voltage restoration is taken into account by the secondary controller:

$$V_{V,i} = G_{PI,V} \left(V_{nom} - \overline{V}_i \right) , \tag{12}$$

where $V_{V,i}$ and $\overline{V}_i$ are the voltage restoration term and estimated average voltage of all BEUs at the *i-th* BEU, respectively; $G_{PI,V}$ is the transfer function of the PI controller for the voltage restoration. If the estimated average voltage $\overline{V}_i$ is considered as the consensus variable, it is calculated by using the consensus algorithm in (1) and (2):

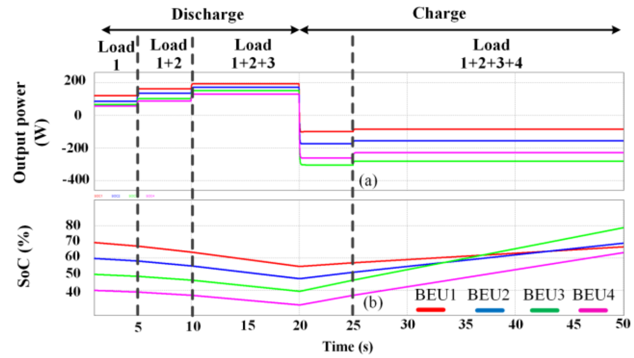

Fig. 5. Simulation results of conventional droop control: (a) Output power, (b) SoC level

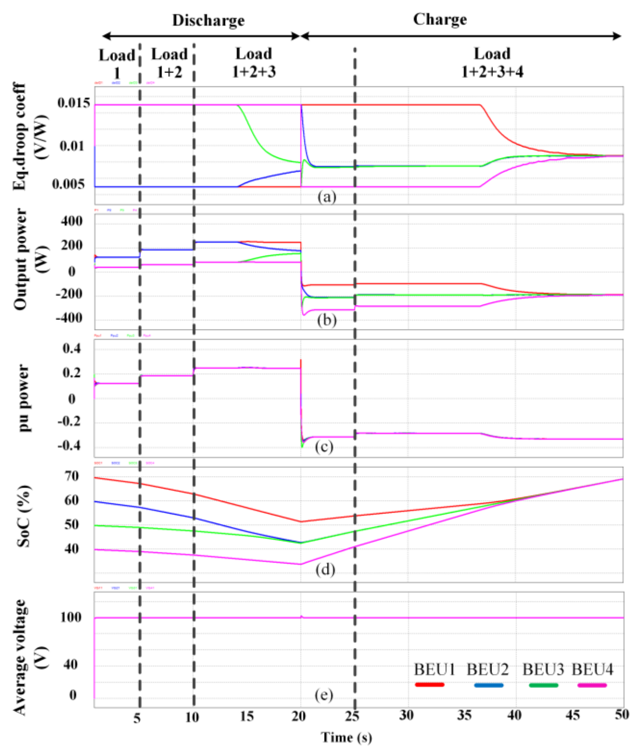

Fig. 6. Simulation results of the proposed method: (a) Equivalent droop coefficient, (b) Output power, (c) pu power, (d) SoC level, (e) Average voltage

$$\begin{aligned} \overline{V}_i(k+1) &= V_i(k) + \varepsilon \sum \delta_{ij}(k+1) \\ \delta_{ij}(k+1) &= \delta_{ij}(k) + a_{ij}\left(\overline{V}_j(k) - \overline{V}_i(k)\right) \end{aligned} \tag{13}$$

From the voltage restoration technique in (12), it guarantees the stable operation of the DC microgrid because the average voltage of all BEUs is restored to the nominal value.

Fig. 2(b) shows the principle of accurate power sharing and voltage restoration for two BEUs in the discharging period. Originally, two BEUs operate at point A1 and A2 on the solid droop lines. After accurate power sharing, the droop lines shift by $\Delta V_{P,1}$ and $\Delta V_{P,2}$, and all operation points move to point A. In addition, because of voltage restoration, the droop lines are shifted upward with the amount of $\Delta V_{V,1}$ and $\Delta V_{V,2}$ to restore the average voltage to the nominal value.

From Fig. 2(b), the proposed control can be expressed in (14), and the overall control scheme is shown in Fig. 3.

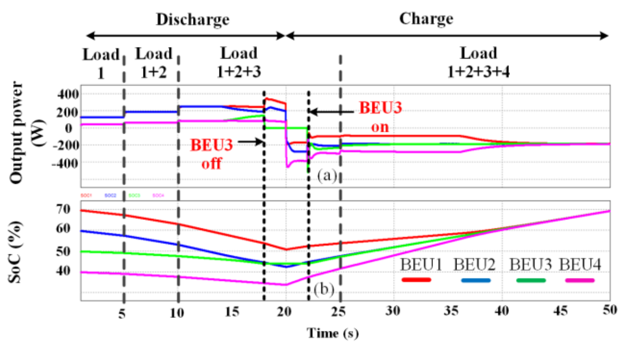

Fig. 7. Plug-and-play capability of the proposed method

$$V_{ref,i} = V_{nom} - d_{eq,i}P_i + \Delta V_{P,i} + \Delta V_{V,i} \quad (14)$$

In Fig. 3, the i-th BEU transfers the information about the estimated average SoC ($\overline{SoC_i}$), per unit power ($p_{pu,i}$) and estimated average voltage ($\overline{V_i}$) with its neighbor BEU via a neighbor-to-neighbor communication network.

IV. Simulation results

In order to evaluate the effectiveness of the proposed control method, we consider the DC microgrid with four BEUs as shown in Fig. 4. From Fig. 4, the communication network has the ring configuration as red-dotted line, and each BEU only communicates with its two neighbors. The parameters of the system are given in Table I. The load condition in the microgrid is changed by means of the resistive load. In Fig. 4, only load 1 is initially connected to the grid, and the loads 2, 3, 4 are connected to the grid, sequentially. The simulation is implemented in discharging and charging sequence of BEUs. During discharging period, only BEUs supply power to the loads. Meanwhile, in charging period, the renewable source supplies around 1500W, which is higher than that of total load power of 750W.

A. Normal operation

Fig. 5 shows the performance of the conventional droop control base on (5). As can be seen, the SoC levels of BEUs can not be balanced because the conventional droop control does not consider the BEUs' SoC.

Fig. 6 shows the performance of the proposed control method in case of discharging and charging. From Fig. 6(a), in discharging period, BEU1 and BEU2 have the highest SoC at the beginning, so their equivalent droop coefficients keep at the minimum values of 0.005 V/W to supply the high power to the microgrid as presented in Fig. 6(b). Meanwhile, BEU3 and BEU4 have the lowest SoC, and their droop coefficients are regulated to set with the highest values of 0.015V/W in order to supply low power to the microgrid. On the other hand, in charging period, as shown in Fig. 6(a), the droop coefficients of BEU, which has the highest SoC, is regulated to keep at maximum value, and that of BEU 4 is the smallest value because it has the lowest SoC. Therefore, from Fig. 6(b), BEU1 absorbs the lowest power and BEU 4 receives the highest power. Due to the accurate power sharing as demonstrated by the equivalent pu power in Fig. 6 (c), the SoC levels of all BEUs are precisely balanced even though the line resistances are different as shown in Fig. 6 (d). Moreover, from Fig. 6(e), the estimated average voltages at BEUs are converged to the same value and restored to the nominal level thanks to the proposed voltage restoration based on the consensus algorithm.

B. Plug-and-play capability

Fig. 7 presents the plug-and-play capability of the proposed method. BEU3 is off at 18s and plugged back at 22s. From 18s to 22s, because of disconnection, the output power of BEU3 is zero, and its SoC level is unchanged. However, when BEU3 is reconnected, the proposed controller has properly updated the SoC regulation for BEU3, and the balanced SOC of all BEUs are finally achieved.

V. Conclusion

This paper proposes the distributed SoC balancing method among distributed BEUs with accurate power sharing based on the consensus algorithm in a DC microgrid. The distributed control algorithm is implemented to estimate the average SoC and the voltage regulation is determined by comparing the per unit power of BEU with those of the neighbors. From the estimated average SoC and the voltage regulation, accurate power sharing is achieved based on the SoC levels of BEUs. As a result, SoC balancing among BEUs is guaranteed regardless of the line resistance difference in the DC microgrid; the BEUs with the higher SoC than the estimated average SoC value supply more power in discharging period and absorb less power during charging period than those with the lower SoC. In addition, a voltage restoration is also carried out to maintain the average voltage of BEUs at the nominal value. The effectiveness of the control method is verified by the simulation.

Acknowledgment

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