

ORIGINAL RESEARCH

Open Access



Hierarchical distributed control for decentralized battery energy storage system based on consensus algorithm with pinning node

Hanqing Yang, Shihan Li, Qi Li* and Weirong Chen

Abstract

A decentralized battery energy storage system (DBESS) is used for stabilizing power fluctuation in DC microgrids. Different state of charge (SoC) among various battery energy storage units (BESU) during operation will reduce batteries' service life. A hierarchical distributed control method is proposed in this paper for SoC balancing and power control according to dispatching center requirement in DBESS. A consensus algorithm with pinning node is employed to allocate power among BESUs in the secondary control whereas in the primary control, the local controller of BESU adjusts output power according to the reference power from secondary control. Part of BESUs are selected to be pinning node for accepting command from dispatching center while other BESUs as following nodes which exchange output power and SoC information with the adjacent nodes through communication network. After calculating reference power of each BESU by adopting consensus algorithm, the power sharing in DBESS is achieved according to their respective SoC of BESUs. Meanwhile, the total output power of DBESS follows the varying requirements of dispatching center. The stability of DBESS is also improved because of having no center controller. The feasibility of the proposed control strategy is validated by simulation results.

Keywords: Decentralized battery energy storage system, Hierarchical distributed control, Consensus algorithm, Pinning node

1 Introduction

Compared with the conventional energy sources, renewable energy sources (RESs) have gained increasing attention due to the advantages of being clean and worldwide distribution [1, 2]. Recently, the concept of microgrid has been proposed for more efficient use of RESs [3, 4]. In particular, DC microgrids have shown to provide simpler structure and control than AC microgrids, because of requiring fewer power conversion stages when integration DC sources such as photovoltaic cells, fuel cells and batteries [5].

However, the intermittent and randomness characteristics of RESs cause problems of power quality and stability in microgrids. In order to ensure the security and stability of the system, decentralized battery energy

storage system (DBESS) has become an importance part of microgrid systems [6].

It is well known that the batteries have higher efficiency and longer service life when their state of charge (SoC) are maintained at a certain range [7]. Thus, it is important that the SoC of each battery energy storage unit (BESU) is kept similar at all-time within the required range. Therefore, the allocation of total power in DBESS should be controlled to avoid overcharging / over-discharging of any of the BESUs.

Several previous studies have been conducted to achieve SoC balancing. A droop control method combining droop coefficient and SoC is proposed in [8] to achieve proportional load power sharing. Reference [9] presents a new droop control method based on voltage scheduling to maintain the SoC of different energy storage units balanced by modifying voltage references. To ensure SoC balancing, a gain-scheduling controller

* Correspondence: liqi0800@163.com

School of Electrical Engineering, Southwest Jiaotong University, PO Box 610031, Chengdu, China

based on fuzzy logic is designed in [10] by adjusting the droop coefficient.

However, there are several limitations of these methods mentioned above when line resistances are considered, as the batteries will operate at different charging/discharging current due to the voltage drops across the line resistances. This will cause the SoC of the BESSs to diverge. Although the centralized control strategy can be used to solve this problem, the required data transmission and communication devices introduce potential system instability [11, 12].

The hierarchical distributed control needs the autonomous control units updating their own states by communicating with adjacent nodes to complete complex tasks together. In [13], a distributed multi-agent based algorithm is proposed to realize SoC balancing by means of voltage scheduling. Reference [14] proposes a sliding mode control strategy based on multi-agent system to improve the converge speed of the existing SoC balancing strategies. However, these methods are not applicable in energy management as the required power is allocated automatically among batteries according to their respective SoC through communicating with adjacent nodes and cannot receive instructions from dispatching center.

The technique of providing the reference values to only a fraction of agents in the network, known as pinning, has been studied in [15, 16]. The pinning-based control can reduce the number of controllers by pinning parts of nodes for a large complex system, which often requires to add controllers to all nodes [17, 18].

In this paper, a hierarchical distributed control method is proposed for balancing SoC and controlling power as required from dispatching center in DBESS. A consensus algorithm with pinning node is employed to allocate power among BESUs in the secondary control, whereas

the local controller of BESU in the primary control adjusts output power according to the reference power from the secondary control.

The rest of the paper is organized as follows. The DBESS is presented in Section 2 whereas Section 3 introduces hierarchical distributed control based on consensus algorithm with pinning node. Simulation of different operation conditions is developed in Section 4 and finally, Section 5 summarizes the paper and draws the conclusion.

2 Decentralized battery energy storage system

A typical DC microgrid configuration with DBESS is presented in Fig. 1. In the DC microgrid, RESs can operate at maximum power point tracking mode, supplying power to the common bus. The DBESS is used to stabilize the power fluctuation and maintain the DC bus voltage within a certain range. When the power generated by RESs is less than the load power demand, the DBESS works in the discharge mode, supplying power to the load together with the RESs. When the generated power is greater than the demanded power, the DBESS works in the charging mode to absorb the excess power from the system.

Typically, droop control is employed in the BESU DC/DC converter for voltage regulation and power sharing. Furthermore, the adaptive droop control based on SoC can dynamically adjust the charge/discharge power of BESU, ensuring all the batteries' SoC to be consistent after operating for a certain period [8–10].

However, there are two limitations by using droop control when considering line resistance. One is the voltage deviation caused by virtual resistance (droop) and line resistance, and the other is the decrease of power sharing accuracy. Adopting adaptive droop

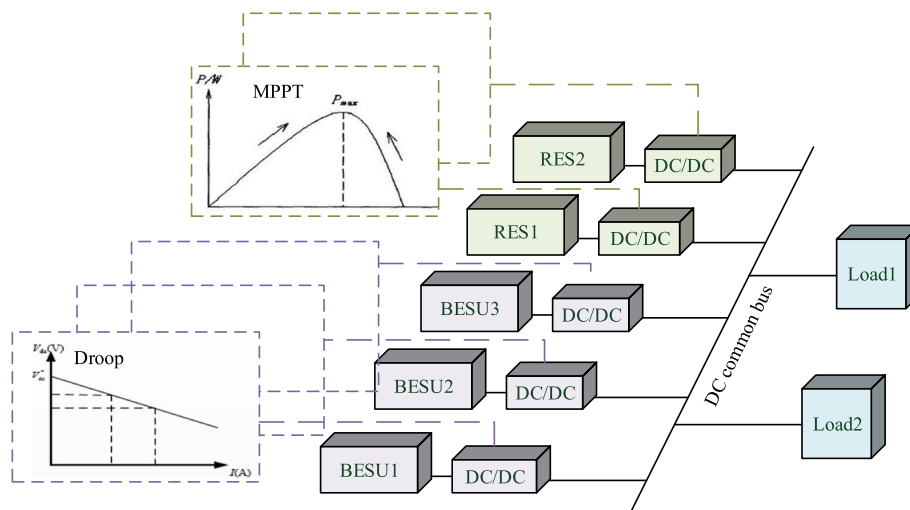


Fig. 1 DC microgrid system with DBESS

control based on SoC in each BESU, the voltage of the DC common bus can be described as:

$$V_{dc} = V_{dc}^* - R_{di} \cdot I_{BESUi} \quad (1)$$

where V_{dc} and V_{dc}^* are the actual and reference voltages of the DC common bus, respectively. R_{di} is the virtual resistance (droop constant) calculated by SoC of the i -th BESU and I_{BESUi} is the output current of the i -th BESU.

When the line resistance is taken into consideration, (1) should be rewritten as:

$$V_{dc} = V_{dc}^* - R_{di} \cdot I_{BESUi} - R_{linei} \cdot I_{BESUi} \quad (2)$$

where R_{linei} stands for the line resistance of the i -th BESU branch.

Taking two BESUs operating in discharging mode as an example, the droop characteristic curves without and with line resistance are shown in Fig. 2a and b, respectively. The initial SoC of BESU1 (SoC_1) is smaller than SoC of BESU2 (SoC_2).

For the case shown in Fig. 2a without line resistance, it is necessary to satisfy $I_{BESU1} < I_{BESU2}$ ($R_{d1} > R_{d2}$), to

ensure that BESU2 with higher SoC outputs a larger discharging current than that of BESU1 with lower SoC. When the line resistances are presented in Fig. 2b, in the case of $R_{d1} + R_{line1} < R_{d2} + R_{line2}$, the BESU1 with smaller SoC will output more power than BESU2.

Therefore, due to the presence of uncertain line resistance, employing the adaptive droop control based on SoC method could potentially lead the BESU with the smallest SoC to a higher discharging rate, resulting in a shorter service life of battery. Therefore, appropriate allocation of total power in DBESS should be achieved to avoid the overcharging/over-discharging of BESUs.

3 Methods

3.1 Hierarchical distributed control

To complete a complex task, it is necessary to divide the task into several simple tasks. So the hierarchical distributed control is employed to divide the whole system into a few autonomous control units to allocate power among BESUs and adjust the output power according to the reference power. The structure of the hierarchical distributed control is shown in Fig. 3, which is divided into three levels including the primary control, the secondary control and the dispatching center.

- 1) The primary control. It controls the voltage and current of BESU according to the control command sent by the secondary control. Meanwhile, it transmits the collected power, SoC and other physical signals to the secondary control.
- 2) The secondary control. It sends the calculated control command by exchanging data with adjacent generation units through preset communication networks.
- 3) Dispatching center. By applying the pinning control to some nodes, the dispatch control of the system can be realized by the coupling relationship between the following nodes and the pinning nodes.

In this paper, the primary control and the secondary control of BESU are studied, so that the BESU can automatically control the charge/discharge power based on their respective SoC conditions. At the same time, the part of secondary control units can accept the command from the dispatching center to realize the ability for the whole DBESS to respond to system dispatching.

3.2 Discrete consensus algorithm with communication delay

Consensus control tends to make some states of all individuals in the distributed system be consistent with each other by exchanging information between the individual and its adjacent ones. Consensus algorithm is a kind of distributed algorithm for consensus control [19, 20]. In recent years, the consensus algorithm has achieved many successes in the group and formation control of space shuttles, and has gradually been used for power system

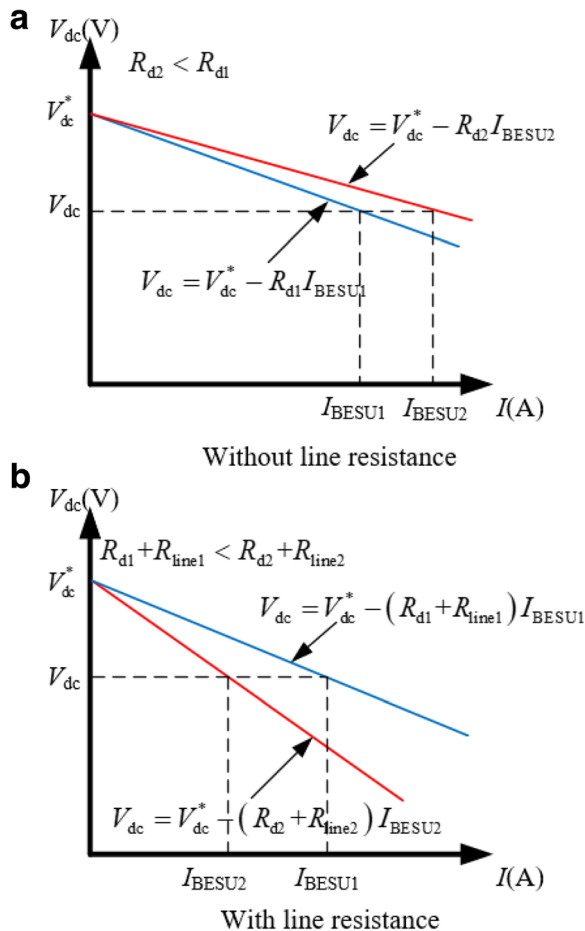


Fig. 2 Droop characteristic curves

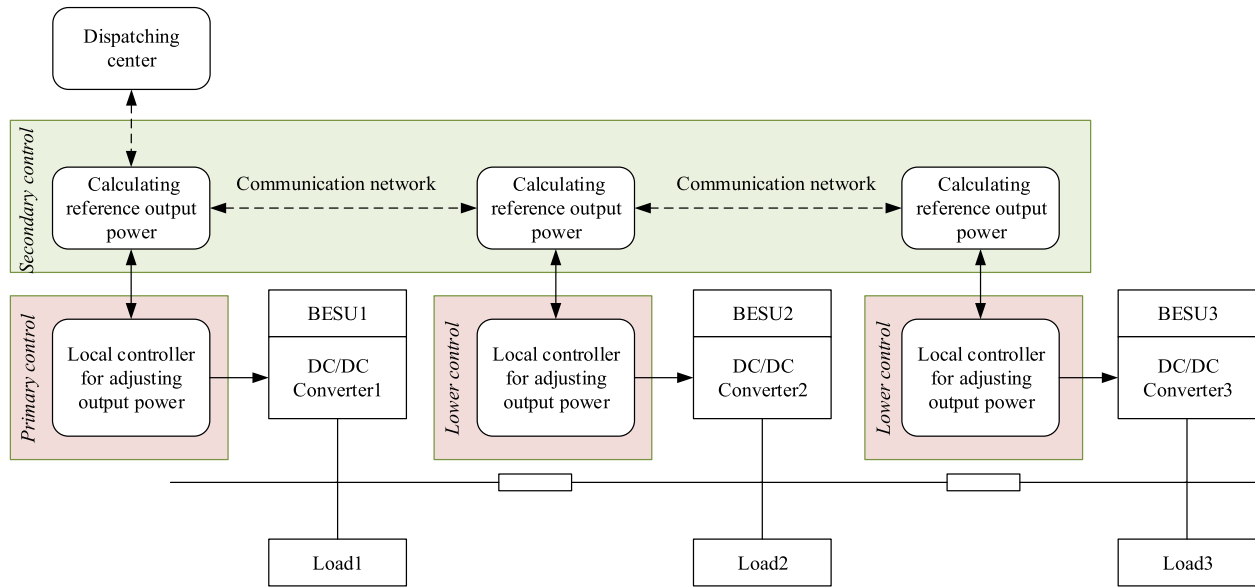


Fig. 3 Structure of the hierarchical distributed control

economic scheduling and hierarchical control. The first-order discrete consensus algorithm is widely used for its advantages of simple convergence condition and fast convergence speed [21].

The BESU can only communicate with its adjacent BESUs. Let x_i denotes the state variable of the i -th BESU, and x_i can represent any physical information, such as voltage, current and SoC. When x_i of all BESUs are the same, the DBESS achieves consensus convergence. The discrete consensus algorithm is shown as:

$$x_i[k+1] = \sum_{j=1}^m d_{ij}x_j[k] \quad (3)$$

where j is an adjacent node of the i -th BESU, d_{ij} is the transfer coefficient between the i -th BESU and its adjacent node j , and m is the number of BESUs.

However, in a real system, it will take some time in the process of signal conversion and transmission. The time required to transmit the signal from adjacent node j to node i is

$$\tau_{ij} = \tau_1 + \tau_2 + \tau_3 \quad (4)$$

where τ_1 is the total time for signal sampling and communication processing, τ_2 is the time of transmitting over the communication line, and τ_3 is the time of converting the received signals by node i .

The communication among all nodes is discrete in time when using the discrete consensus algorithm and thus, there will be a time interval T between two communications. When T is greater than the communication delay τ_{ij} , the communication delay does not have

any effect on system. In the case of τ_{ij} being greater than T , the communication delay will impact on the consensus algorithm, and the corresponding algorithm expression should be rewritten as:

$$x_i[k+1] = x_i[k] + \sum_{j=1, j \neq i}^m d_{ij}x_j[k-1] \quad (5)$$

Equations (3) and (5) can describe and simulate all the operation conditions whereas (3) stands for normal operation condition with small communication delay and (5) represents condition with larger communication delay.

The transfer coefficient d_{ij} can affect the convergence and convergence speed of consensus algorithm. When $D = [d_{ij}]$ is a random matrix, x_i can converge in some specific conditions [22]. If D is a double random matrix, x_i can converge to the average of the system initial value. In order to improve the reliability of discrete consensus algorithm, the Metropolis method are employed to construct a double random matrix D with non-zero diagonal elements [23]. The Metropolis method is describe as:

$$d_{ij} = \begin{cases} \frac{1}{\max(n_i, n_j) + 1} & j \in N_i \\ 1 - \sum_{j \in N_i} \frac{1}{\max(n_i, n_j) + 1} & i = j \\ 0 & \text{others} \end{cases} \quad (6)$$

where n_i and n_j are the respective adjacent numbers of node i and j , $\max(n_i, n_j)$ stands for the maximum value of n_i and n_j .

3.3 Consensus control with pinning node

The main principle of the consensus control with pinning node is to consider the DBESS shown in Fig. 3 as a network-connected distributed system. Each BESU contains the primary control and the secondary control. The secondary control of BESU which is selected as the pinning node, can receive the dispatching command from the system. The principle of power allocation is that the charge/discharge power of each BESU is the same as the ratio of the power to their respective SoC.

The SoC of BESU needs to be obtained first. For the many published battery SoC detecting methods, the current integration method is employed in this paper to calculate the SoC as [24]:

$$SoC_i = SoC_i^* - \frac{1}{C_{ei}} \int I_{bi} dt \quad (7)$$

where I_{bi} , SoC_i^* , C_{ei} are the output current, initial SoC and rated capacity of the battery of the i -th BESU, respectively.

Neglecting the power loss of the DC/DC converter, there is

$$P_i = P_{ini} = U_{ini} I_{bi} \quad (8)$$

where U_{ini} , P_i , P_{ini} are the output voltage, output power and input power of the DC/DC converter of the i -th BESU, respectively.

The expression for detecting SoC can be rewritten by combining (7) and (8) as:

$$SoC_i = SoC_i^* - \frac{1}{C_{ei} U_{in}} \int P_i dt \quad (9)$$

The ratio is then defined in the respective charging and discharging operation states as:

$$r_{chari}[k] = P_{BESUi}[k] \cdot SoC_i[k] \quad (10)$$

$$r_{disci}[k] = \frac{P_{BESUi}[k]}{SoC_i[k]} \quad (11)$$

where $P_{BESUi}[k]$ and $SoC_i[k]$ are the input/output power and SoC of the i -th BESU, and $r_{chari}[k]$ and $r_{disci}[k]$ are the charging and discharging ratios of the i -th BESU. $P_{BESUi}[k] < 0$ stands for charging operation while $P_{BESUi}[k] > 0$ for discharging operation. The ratio of each BESU will tend to be consistent after several iterations by using consensus algorithm. Thus, the purpose of power distribution is achieved.

There are some bases for selecting the BESU to receive power command, e.g. the distance from dispatching center and reliability of communication network. In this paper, it is assumed that the nearest BESU to dispatch center is BESU1 which is selected to receive the reference power information from dispatching center

through network communication, and is the pinning node. The remaining BESUs in the DBESS which do not need to have network connection to the dispatching center are the following node. Figure 4 shows the flow chart of power allocation in a sampling period.

At the beginning of each sampling period, the initial power values of the pinning node and following node are set as:

$$\begin{cases} P_{BESU1}[0] = P_{all} \\ P_{BESUi}[0] = 0 \end{cases} \quad (12)$$

$$\begin{cases} SoC_1[0] = SoC_1(0) \\ SoC_i[0] = SoC_i(0) \end{cases} \quad (13)$$

where P_{all} is the reference power value from dispatching center. $P_{all} < 0$ stands for charging operation while $P_{all} > 0$ represents discharging operation.

Then, the discrete consensus algorithm is used to iterate the P_{BESUi} and SoC_i as:

$$P_{BESUi}[k+1] = P_{BESUi}[k] + \sum_{j=1, j \neq i}^m d_{ij} P_{BESUj}[k-1] \quad (14)$$

$$SoC_i[k+1] = SoC_i[k] + \sum_{j=1, j \neq i}^m d_{ij} SoC_j[k-1] \quad (15)$$

After several iterations, (14) and (15) will converge to the average of initial values as:

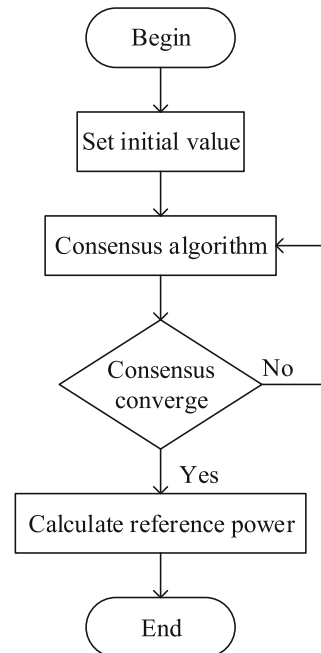


Fig. 4 Flow chart of power allocating

$$P_{\text{BESU}i}^* = \lim_{k \rightarrow +\infty} P_{\text{BESU}i}[k] = \frac{1}{n} \sum_{i=1}^n P_{\text{BESU}i}[0] = \frac{P_{\text{all}}}{n} \quad (16)$$

$$\text{SoC}_i^* = \lim_{k \rightarrow +\infty} \text{SoC}_i[k] = \frac{1}{n} \sum_{i=1}^n \text{SoC}_i(0) \quad (17)$$

Therefore, the charging and discharging ratios of the i -th BESU will also converge to constants as:

$$r_{\text{char}i}^* = P_{\text{BESU}i}^* \cdot \text{SoC}_i^* = P_{\text{all}} \cdot \sum_{i=1}^n \text{SoC}_i(0) / n^2 \quad (18)$$

$$r_{\text{disc}i}^* = P_{\text{BESU}i}^* / \text{SoC}_i^* = P_{\text{all}} / \sum_{i=1}^n \text{SoC}_i(0) \quad (19)$$

Finally, the input power and output power can be calculated by the ratios of charging and discharging operation:

$$P_{\text{BESU}i}^* = \begin{cases} r_{\text{char}i}^* / \text{SoC}_i & \text{charging} \\ r_{\text{disc}i}^* \cdot \text{SoC}_i & \text{discharging} \end{cases} \quad (20)$$

The above equation describes how to obtain the power reference value of each BESU by the consensus control with pinning node. This method is a distributed algorithm as each BESU gets its own charge/discharge power reference value according to their own information and information of its adjacent nodes. The SoC of different BESUs can be balanced and the total output power of DBESS follows dispatching requirement.

4 Results and discussion

In order to verify the proposed hierarchical distributed control based on consensus algorithm with pinning node, the simulation model shown in Fig. 5a is established, which consists of three battery branches with different line resistances. The model parameters are shown in Table 1 and the communication network topology is shown in Fig. 5b. However, other communication network topologies can also be used as long as they satisfy the requirement of connection. Different network topologies only affect the speed of consistency convergence.

In this paper, matrix D is constructed by (6) and the scheme of self-organization mechanism is designed. In this case, it is assumed that the pinning node is reliable and has been involved all the time. The self-organization mechanism is mainly used to constrain the switching of the following nodes.

Taking BESU2 as an example, when BESU2 needs to be connected in, BESU2 will send incoming packets to BESU1 and BESU3, and then update its own matrix D . After receiving the incoming message, BESU1 and BESU3 broadcast the latest neighbor messages and update their own matrix D elements. Their own matrix D are all updated by (6), ensuring that matrix D is still a double random matrix with non-zero diagonal elements.

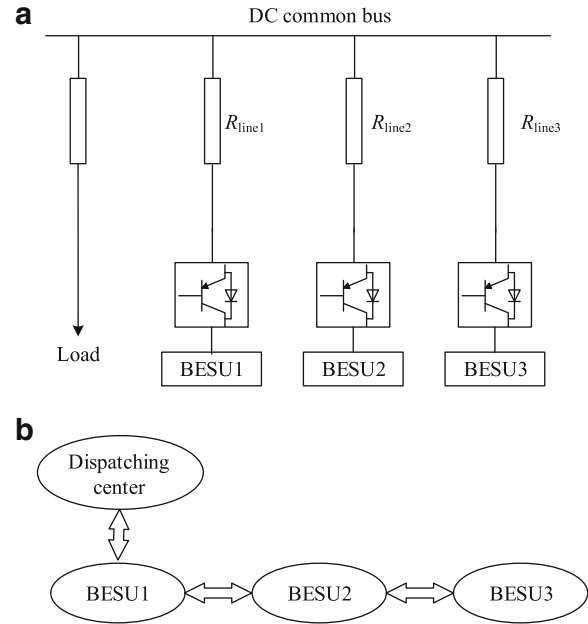


Fig. 5 Configuration and communication topology of DBESS

According to the self-organization mechanism, the BESU can connect or disconnect their neighbor nodes without affecting the system operation.

Figure 6 shows the simulation results of charging operation, and the total power of DBESS is given by dispatching center and varies with time. The initial SoC of BESU1, BESU2 and BESU3 are 40%, 45%, 50%, respectively. Figure 6a and 6b show the SoC and charging current of each BESU, and Fig. 6c presents the average voltage of DBESS.

In 0~100 s, the total power of DBESS given by dispatching center is 800 W. At the beginning of operation, BESU1 has the smallest SoC and absorbs most of the power. At 100 s, the SoC of BESU1 and BESU2 become almost identical and thus, the charging currents also tend to be equal. During the time of 100~200 s, the total power of DBESS given by dispatching center is reduced to 500 W. The charging currents of all BESUs are reduced accordingly. At 200 s the difference of SoC

Table 1 System parameters

	Parameters	value
Line resistance	$R_{\text{line}1}$ (Ω)	0.5
	$R_{\text{line}2}$ (Ω)	0.8
	$R_{\text{line}3}$ (Ω)	0.9
BESU	type	Lead-acid battery
	Rated voltage (V)	24
	Rated capacity (Ah)	5
DC bus	Rated voltage (V)	48

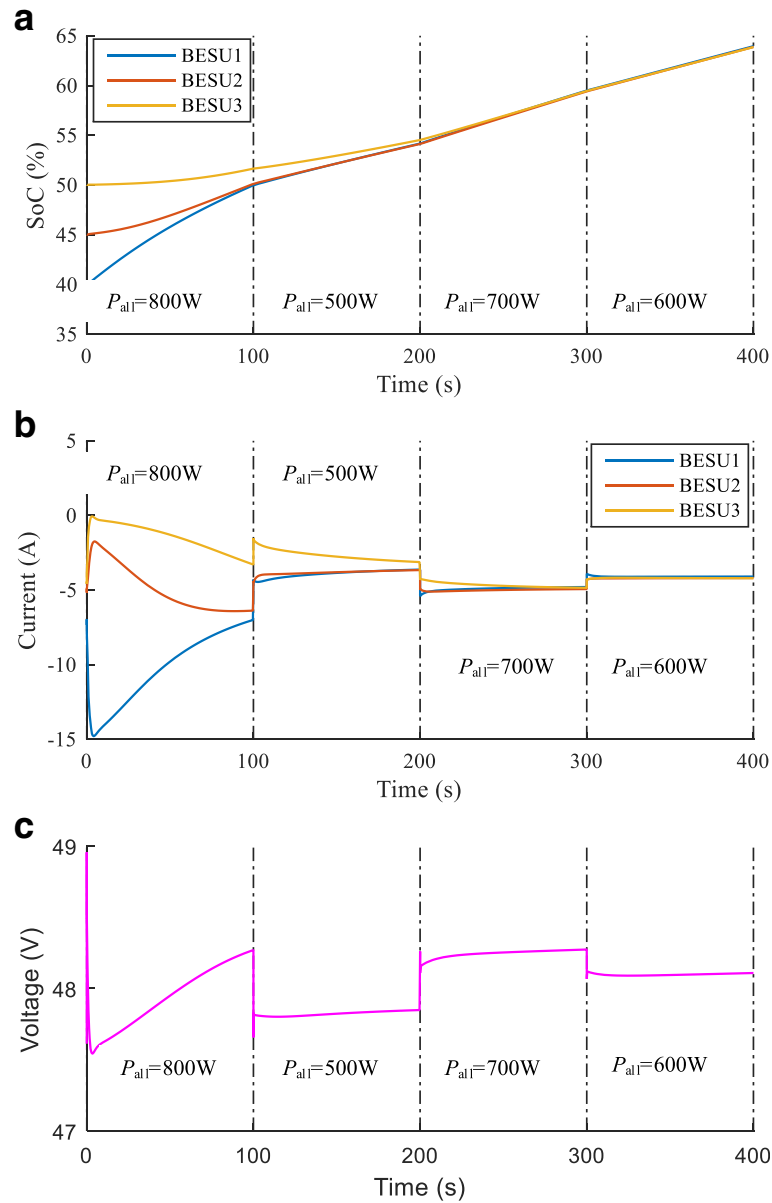


Fig. 6 Simulation results in charging operation

between BESU1/BESU2 and BESU3 almost disappears. In 200~300 s, the total power of DBESS given by dispatching center is 700 W. During this period, the SoC of these three BESUs is balanced and so as the charging currents. Although the total power changes to 600 W at 300 s, the charging ratios of all three BESUs stay the same. According to Fig. 6c, the voltage is maintained in the range of 48 ± 0.5 V during the operation.

As seen from Fig. 6, in the charging operation, the priority is given to the BESU with the lowest SoC to obtain a larger charging current. The proposed control strategy can balance SoC and control output power varying with dispatching center requirements in DBESS.

Figure 7 shows the simulation results of discharging operation, and the varying total power of DBESS is given by dispatching center. The initial SoC of BESU1, BESU2 and BESU3 are 75%, 70%, 65%, respectively. Figure 7a and b show the SoC and discharging current of each BESU, and Fig. 7c presents the average voltage of DBESS.

In 0~100 s, the total power of DBESS given by dispatching center is 500 W. At the beginning of operation, BESU1 has the largest SoC and produces most of the output power. At 100 s, the difference of SoC among the BESUs is reduced to be less than 5%. During 100~200 s, the total power of DBESS given by dispatching center is increased to 700 W and thus, the discharging currents

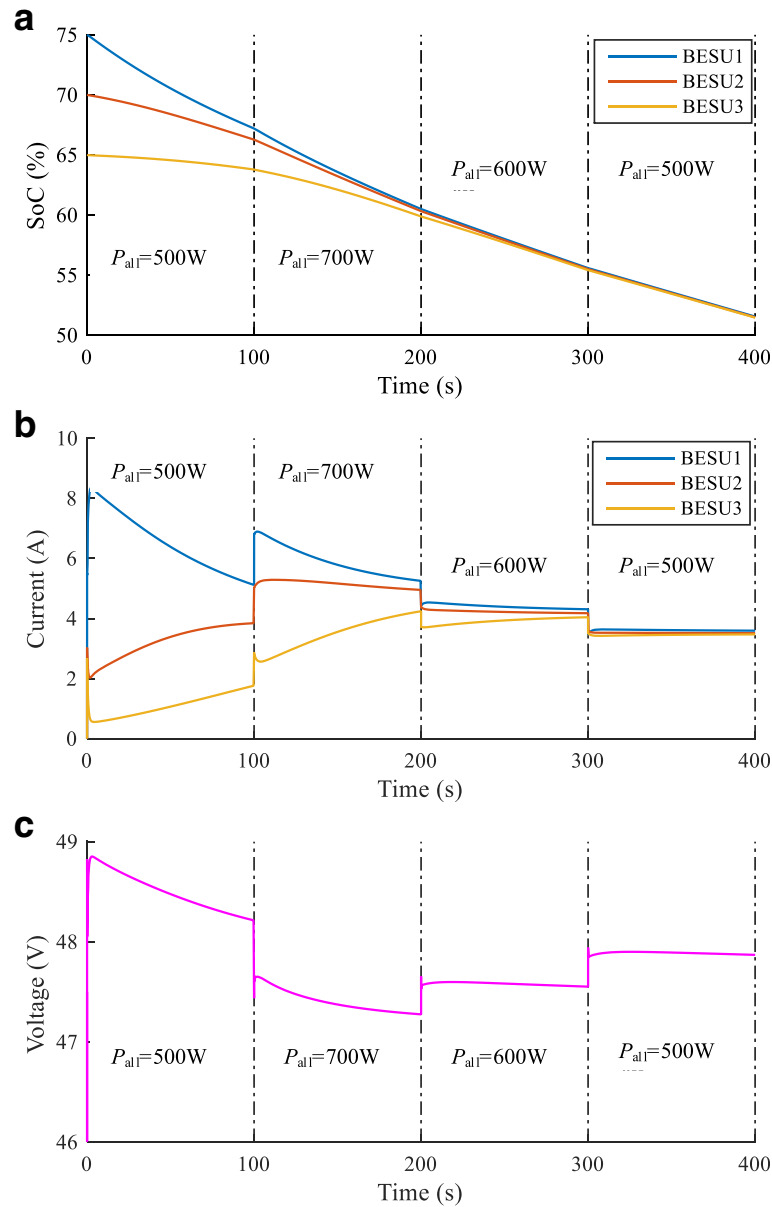


Fig. 7 Simulation results in discharging operation

of all BESUs are also increased. At 200 s, the SoC difference among the three BESUs is small and therefore, their discharging currents also become similar. In 200~300 s, the total power of DBESS given by dispatching center is 600 W whereas it reduces to 500 W at 300 s. During this period, the BESU with the highest SoC always provide more power than the BESU with the smallest SoC. Finally, SoC balancing is achieved at 400 s. According to Fig. 7c, the voltage is maintained in the range of 48 ± 1 V during the whole operation.

As seen from Fig. 7, in the discharging operation, although the total power demanded varies, the BESU with the lowest SoC always has less discharging current. SoC

balancing and controlling output power according to dispatching center in discharging operation are realized by adopting the proposed control strategy.

5 Conclusions

To address the problems related to the sharing accuracy of the current methods considering the line resistance, a hierarchical distributed control is proposed to realize SOC balancing using consensus algorithm in decentralized battery energy storage system. The proposed control strategy can also change the total output power in DBESS according to the requirements of dispatching center by pinning partial secondary control units of BESU. The simulation

results in both charging and discharging operation validate the feasibility of the proposed control strategy.

Authors' contributions

HY conceived and designed the study. HY and SL performed the experiments. HY, SL and QL wrote the paper. HY, SL, QL and WC reviewed and edited the manuscript. All authors read and approve the manuscript. The part of establishing DBESS model was supported by National Natural Science Foundation of China (61473238, 51407146), the primary droop control analysis got support of Sichuan Provincial Youth Science and Technology Fund (2015JQ0016), and the part of distributed consensus algorithm was supported by Doctoral Innovation Funds of Southwest Jiaotong University (D-CX201714).

Competing interests

The authors declare that they have no competing interests.

Received: 29 March 2017 Accepted: 2 February 2018

Published online: 27 February 2018

References

- Li, Q., Chen, W., Liu, Z., et al. (2015). Development of energy management system based on a power sharing strategy for a fuel cell-battery-supercapacitor hybrid tramway. *J Power Sources*, 279(279), 267–280.
- Xin, H., Lu, Z., Liu, Y., et al. (2014). A center-free control strategy for the coordination of multiple photovoltaic generators. *Smart Grid IEEE Trans*, 5(3), 1262–1269.
- Shen, C. (2013). Wu, et al. multi-stage under frequency load shedding for islanded microgrid with equivalent inertia constant analysis. *Int J Electr Power Energy Syst*, 46(1), 36–39.
- Guo, W., & Mu, L. (2016). Control principles of micro-source inverters used in microgrid. *Prot Control Mod Power Syst*, 1(1), 5.
- Zhu, X., Liu, J., Liu, Y., Zhou, W., Sun, Z., & Jin, Y. (2014). The study of micro-grid control strategy contained unbalanced load based on sliding-mode variable structure. *IEEE International Conference on Power System Technology*, pp. 3328–3334.
- Gu, W., Wu, Z., Bo, R., et al. (2014). Modeling, planning and optimal energy management of combined cooling, heating and power microgrid: A review. *Int J Electr Power Energy Syst*, 54(1), 26–37.
- Hu, X., Sun, F., & Zou, Y. (2013). Comparison between two model-based algorithms for li-ion battery SOC estimation in electric vehicles. *Simul Model Pract Theory*, 34(4), 1–11.
- Lu, X., Sun, K., Guerrero, J. M., & Vasquez, J. C. (2012). SoC-based droop method for distributed energy storage in DC microgrid applications. *IEEE International Symposium on Industrial Electronics*, pp.1640–1645.
- Li, C., Dragicevic, T., Diaz, N. L., Vasquez, J. C., & Guerrero, J. M. (2014). Voltage scheduling droop control for State-of-Charge balance of distributed energy storage in DC microgrids. *IEEE Energy Conference*, pp.1310–1314.
- Diaz, N. L., Dragicevic, T., Vasquez, J. C., & Guerrero, J. M. (2014). Fuzzy-logic-based gain-scheduling control for state-of-charge balance of distributed energy storage systems for DC microgrids. *IEEE Applied Power Electronics Conference and Exposition*, pp. 2171–2176.
- Meng, L., Dragicevic, T., Vasquez, J., Guerrero, J., & Sanseverino, E. R. (2015). Hierarchical control with virtual resistance optimization for efficiency enhancement and State-of-Charge balancing in DC microgrids. *IEEE First International Conference on Dc Microgrids*, pp. 1–6.
- Dragicevic, T., Guerrero, J. M., Vasquez, J. C., et al. (2014). Supervisory control of an adaptive-droop regulated DC microgrid with battery management capability. *Power Electron IEEE Trans*, 29(2), 695–706.
- Li, C., Dragicevic, T., Plaza, M. G., Andrade, F., Vasquez, J. C., & Guerrero, J. M. (2015). Multiagent based distributed control for state-of-charge balance of distributed energy storage in DC microgrids. *IEEE Conference on Industrial Electronics Society*, pp. 2180–2184.
- Morstyn, T., Savkin, A., Hredzak, B., & Agelidis, V. (2017). Multi-agent sliding mode control for state of charge balancing between battery energy storage systems distributed in a dc microgrid. *IEEE Transactions on Smart Grid*, PP. (99), 1–1.
- Su, H., Rong, Z., Chen, M. Z., Wang, X., Chen, G., & Wang, H. (2013). Decentralized adaptive pinning control for cluster synchronization of complex dynamical networks. *IEEE Transactions on Systems Man & Cybernetics*, 43(1), 394–399.
- Li, X., Wang, X., & Chen, G. (2004). Pinning a complex dynamical network to its equilibrium. *IEEE Trans Circuits Syst Regular Papers*, 51(10), 2074–2087.
- Talebi M, Manaffam S, Jain A K, et al. Intelligent pinning based cooperative secondary control of distributed generators for microgrid in islanding operation mode. 2016.
- Liu, W., Gu, W., Sheng, W., Meng, X., Xue, S., & Chen, M. (2016). Pinning-based distributed cooperative control for autonomous microgrids under uncertain communication topologies. *IEEE Transactions on Power Systems*, 31(2), 1320–1329.
- Chen, C., Zhang, B., Lu, Q., et al. (2015). A consensus algorithm based on nearest second-order Neighbors' information. *IFAC-PapersOnLine*, 48(11), 545–550.
- Zhang, Z., & Chow, M. Y. (2012). Convergence analysis of the incremental cost consensus algorithm under different communication network topologies in a smart grid. *Power Syst IEEE Trans*, 27(4), 1761–1768.
- Xu, Y., & Liu, W. (2011). Novel multiagent based load restoration algorithm for microgrids. *IEEE Trans Smart Grid*, 2(1), 152–161.
- Kriegledler, M., Oung, R., & D'Andrea, R. (2013). Asynchronous implementation of a distributed average consensus algorithm. *IEEE International Conference on Intelligent Robots and Systems*, pp. 1836–1841.
- Guerrero, J. M., Vasquez, J. C., Matas, J., et al. (2011). Hierarchical control of droop-controlled AC and DC microgrids—A general approach toward standardization. *IEEE Trans Ind Electron*, 58(1), 158–172.
- Bhangu, B. S., Bentley, P., Stone, D. A., et al. (2005). Nonlinear observers for predicting state-of-charge and state-of-health of lead-acid batteries for hybrid-electric vehicles. *Vehicular Technol IEEE Trans*, 54(3), 783–794.

Submit your manuscript to a SpringerOpen[®] journal and benefit from:

- Convenient online submission
- Rigorous peer review
- Open access: articles freely available online
- High visibility within the field
- Retaining the copyright to your article

Submit your next manuscript at ► springeropen.com