Optimal Operation of Energy Storage Units with Efficiency Improvement and State of Charge Balance

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Optimal Operation of Energy Storage Units with Efficiency Improvement and State of Charge Balance

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[Φ]*Abstract* -- This paper proposes an optimal energy storage units (ESUs) operation strategy with efficiency improvement and state of charge (SoC) balance by considering converter characters and network loss. First, the optimal power-sharing ratio considering minimized power loss of paralleled ESUs is obtained with the Lagrange Multiplier Method. Second, the optimal power-sharing ratio with SoC balance of ESUs is obtained. On the basis of it, the optimal operation strategy of paralleled ESUs with efficiency improvement and SoC balance is proposed. The power-sharing ratio of ESUs changes actively according to system operation status. Under the proposed control strategy, the difference in the SoC of each paralleled energy storage unit can be controlled within a desired range. Meanwhile, the system efficiency can be improved. In that case, the system's overall performance can be improved. The effectiveness of the proposed strategy is verified through the real-time simulation with RT-Lab. The proposed control strategy can enhance ESU operation performance with efficiency improvement and SoC balance.

***Index Terms*-- Energy storage unit, optimal operation, efficiency improvement, SoC balance.**

I. Introduction

WITH d the rapid development of renewable energy technologies, the energy storage units (ESUs) have been intensively concerned. As an important instrumental component in renewable energy systems, ESUs are increasingly used for power regulation and power balance [1]. Moreover, it can provide support to critical loads in renewable energy-dominated system. Commonly, ESUs can be connected in paralleled to increase system capacity [2]. The unbalanced state of charge (SoC) of ESUs may weaken reliability, thereby reducing system lifetime [3]. To ensure the reliable operation of ESUs, state of charge (SoC) balance issue is considered.

The existing SoC balance methods mainly concern design of equalization circuits and control strategies [4]. An integrated cascade bidirectional DC-DC converter architecture is proposed in [5]. It can realize the equalization of cells with different voltage polarities, which improves converter reliability. A decentralized SOC balancing method for cascaded-type energy storage systems under two-time scale characteristics is proposed in [6]. A hierarchical SoC balance method for a multi-input single-output converter is proposed in [7], which can achieve SoC balance at either cell level or module level. With the scale of microgrids increasing, the line resistance between ESUs and bus cannot be ignored. To increase the ESUs SoC balance effect in large-scale microgrids, accurate power-sharing with SOC balance considering cable resistance is proposed in [8], [9]. To increase the microgrid performance, a master-slave coordinate control of battery energy storage systems is proposed in [10]. The master units are used to support DC bus voltage. Meanwhile, slave units are operated with SoC-based droop control to avoid overcharging and over-discharging. Adaptive droop control is widely used to achieve SoC balance in ESUs [11]- [13], which can adjust ESU output according to difference between SoC and SoC average value by tuning droop coefficient. Adaptive droop control to perform voltage regulation in DC microgrid consisting of photovoltaic and battery is proposed in [14]. A cooperative cyber network is used to enhance control strategy. A dynamic consensus algorithm-based secondary control with an autonomous current-sharing strategy is proposed in [15] to balance SoC by adjusting virtual resistance.

In addition to energy storage components such as batteries, power converter is also an essential part of the ESU. The efficiency priority operation of the paralleled converter is well discussed in [16]-[18]. Due to different designs and aging levels, the efficiency operating point of paralleled power converters is not only allocated based on converter capacity. The efficiency of paralleled converters changes according to the power-sharing ratio [19]. Meanwhile, the line resistance can also affect the efficiency of paralleled converters [20]. The existing SoC balance methods are conducted by changing power-sharing between ESUs. However, it changes the efficiency of paralleled converters in this progress. Since the optimal power sharing ratio with SoC balance and efficiency operation is hardly the same, the paralleled ESUs operation with SoC balance may lead to a decrease in system efficiency.

The existing ESUs operation strategies mainly focus on control strategies of SoC balance, while neglecting operation performance of converters in ESUs. The optimal control strategy for ESUs with both efficiency improvement and SOC balance is merely addressed. Therefore, this article presents a decentralized optimal operation strategy to achieve SoC balance in a desired range while improving the efficiency for EUSs.

The rest of this paper is organized as follows. In Section II, the efficiency model of ESUs and the SoC model are established. In Section III, optimal power sharing between

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paralleled ESUs is achieved by combining efficiency improvement and SoC balance control. The optimal objective is changed adaptively according to system operation status. The effectiveness of the proposed high efficiency SoC balance control strategy is validated through real-time simulation in Section IV. The conclusion is drawn in Section V.

II. SYSTEM DESCRIPTION AND MODELLING

In this section, the efficiency model of ESU, including battery converter and line resistance is established. Then, the relationship between converter output power and battery SoC is established. The topology of the DC microgrid system with ESUs is shown in Fig. 1.

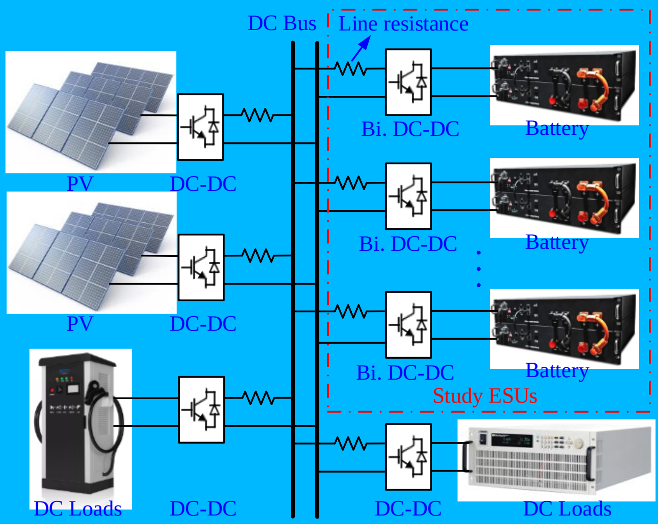

Fig. 1. The topology of the exemplified DC microgrid with paralleled ESUs.

The efficiency of ESU includes battery efficiency and converter efficiency considering line resistance. Due to the small inside resistance, the power loss on the battery can be ignored [8]. The converter power loss model can be established as [16]- [18]

$$P_{\mathrm{loss\_con\_}i} = a_i P_{\mathrm{o}i}^2 + b_i P_{\mathrm{o}i} + c_i \tag{1}$$

where $P_{\mathrm{loss\_con\_}i}$ is the power loss of the i-th converter, $P_{\mathrm{o}i}$ is the output power of the i-th converter, a_i , b_i and c_i are the coefficients of converter power loss.

The power loss coefficients can be obtained by fitting the power loss curves. The converter efficiency η_i can be express as

$$\eta_i = \frac{P_{\mathrm{o}i}}{P_{\mathrm{o}i} + P_{\mathrm{loss\_}i}} \tag{2}$$

$$P_{\mathrm{o}i} = V_{\mathrm{o}i} i_{\mathrm{o}i} \tag{3}$$

where $V_{\mathrm{o}i}$ is the i-th converter output voltage, $i_{\mathrm{o}i}$ is the i-th converter output current.

The network loss $P_{\mathrm{loss\_line\_}i}$ can be calculated with

$$P_{\mathrm{loss\_line\_}i} = \left(\frac{R_{\mathrm{line\_}i}}{V_{\mathrm{o}i}^2}\right) P_{\mathrm{o}i}^2 \tag{4}$$

where $R_{\mathrm{line\_}i}$ is the line resistance of the i-th ESU corresponding line.

The total loss of the i-th ESU, including converter loss and transfer loss can be represented as

$$\begin{aligned} P_{\mathrm{loss\_}i} &= P_{\mathrm{loss\_con\_}i} + P_{\mathrm{loss\_line\_}i} \\ &= \left(a_i + \frac{R_{\mathrm{line\_}i}}{V_{\mathrm{o}i}{}^2}\right) P_{\mathrm{o}i}^2 + b_i P_{\mathrm{o}i} + c_i \end{aligned} \tag{5}$$

The total power loss of the energy storage system $P_{\mathrm{loss\_sys}}$ including n paralleled ESUs can be established as

$$P_{\mathrm{loss\_sys}} = \sum_{i=1}^{n} P_{\mathrm{loss\_}i} \; . \tag{6}$$

The energy storage system load including n paralleled ESUs $P_{\mathrm{load\_sys}}$ can be represented as

$$P_{\mathrm{load\_sys}} = \sum_{i=1}^{n} P_{\mathrm{o}i} \; . \tag{7}$$

The efficiency of energy storage systems including n-paralleled ESUs η_{sys} can be represented as

$$\eta_{\mathrm{sys}} = \frac{P_{\mathrm{load\_sys}}}{P_{\mathrm{load\_sys}} + P_{\mathrm{loss\_sys}}} \; . \tag{8}$$

The Coulomb Counting method is widely used to describe the SoC of battery [8]- [13]. According to the Coulomb Counting method, the SoC can be calculated with

$$SoC_i(t) = SoC_i(t_0) - \frac{1}{C_i}\int_{t_0}^{t+t_0} i_{\mathrm{bat\_}i}\,\mathrm{d}t \tag{9}$$

where $SoC_i(t_0)$ is the initial SoC of the i-th battery, C_i is the capacity of the i-th battery, $i_{\mathrm{bat\_}i}$ is the charging/discharging current of the i-th battery.

The SoC mathematic model can be established as

$$SoC_i(t) = SoC_i(t_0) - \frac{1}{C_i V_{\mathrm{o}i}}\int_{t_0}^{t+t_0} P_{\mathrm{bat\_}i}\,\mathrm{d}t \tag{10}$$

where $V_{\mathrm{o}i}$ is the i-th converter output voltage, $P_{\mathrm{bat\_}i}$ is the power of the i-th battery.

III. THE PROPOSED CONTROL STRATEGY

A. ESUs operation with SoC balance

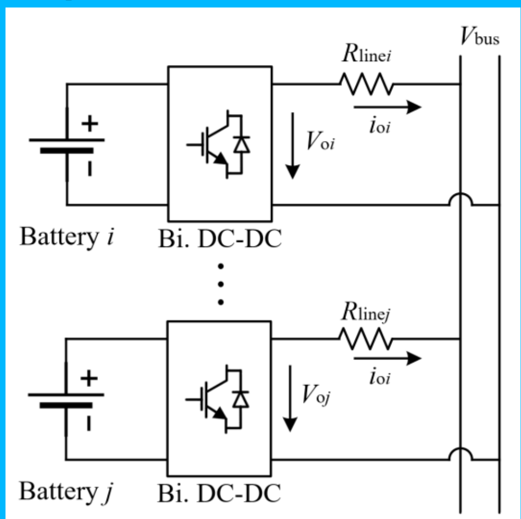

Fig. 2. Paralleled ESUs topology.

The topology of paralleled ESUs is shown in Fig. 2. According to Kirchhoff's law, the relation between converter output voltage V_{oi}, converter reference voltage V_{ref}, bus voltage V_{bus}, converter droop coefficient R_{di}, line resistance R_{linei}, and converter output current i_{oi} can be represented as (11)-(12)

$$V_{oi} = V_{ref} - R_{di} i_{oi} \tag{11}$$

$$V_{bus} = V_{oi} - R_{linei} i_{oi} \tag{12}$$

The converter power of *i*-th ESU can be represented as

$$P_{oi} = V_{oi} \frac{V_{ref} - V_{bus}}{R_{linei} + R_{di}}. \tag{13}$$

To perform SoC balance of ESUs, the ESUs should have the same SoC as well as the same change rate of SoC. According to the SOC mathematic model in (10), the SoC change rate can be represented as

$$SoC'_{(i)} = -\frac{P_{bat\_i}}{C_i V_{oi}} \tag{14}$$

Combined with (13), the power-sharing ratio with SoC balance, considering the influence of cable resistance, is given as

$$\frac{SoC'_i}{SoC'_j} = \frac{P_{oi}}{P_{oj}} = \frac{C_i \left(R_{linei} + R_{di}\right)}{C_j \left(R_{linej} + R_{dj}\right)}. \tag{15}$$

The SoC balance operation point for individual ESU is

$$\frac{1}{C_i \left(R_{linei} + R_{di}\right)} P_{oi} = \frac{1}{C_j \left(R_{linej} + R_{dj}\right)} P_{oj}. \tag{16}$$

B. ESUs Efficiency operation

The efficient operation of paralleled ESUs can be achieved with minimal ESUs total loss. The system-level efficiency operation can be represented as

$$\min\left(S = \sum_{i=1}^{n} P_{lossi}\right) \tag{17}$$

$$\text{s.t.} \sum_{i=1}^{n} P_{oi} = P_{sys\_load}\ .$$

The Lagrange function is used to obtain the minimal paralleled ESUs total power loss as

$$L = \sum_{i=1}^{N} P_{lossi} + \lambda (P_{Load} - \sum_{i=1}^{N} P_{oi}) \tag{18}$$

where λ is the Lagrange multiplier. The system efficiency operation point can be obtained by solving the following equation

$$\begin{cases} \dfrac{\partial S}{\partial P_{o1}} = \dfrac{\partial S}{\partial P_{o2}} = \cdots = \dfrac{\partial S}{\partial P_{oN}} = 0 \\ \dfrac{\partial S}{\partial \lambda} = \sum_{i=1}^{n} P_{oi} - P_{sys\_load} = 0. \end{cases} \tag{19}$$

By solving the (4), the efficiency operation point for paralleled ESUs is

$$2a_i P_{oi} + b_i = 2a_j P_{oj} + b_j\ . \tag{20}$$

C. The proposed ESUs optimal operation strategy with efficiency improvement and SoC balance

According to the analysis above, the power-sharing with SoC balance fails to achieve optimal operation of paralleled ESUs. In that case, the exact SoC balance may not be suited for long-term operation. The proposed optimal operation strategy combines the system efficiency operation and SoC balance operation.

To achieve the optimal operation for paralleled ESUs, the coefficient is introduced as

$$\alpha_i = \begin{cases} 1, & 0 \le \left|SoC_i - SoC_{ave}\right| < \Delta SoC_{min} \\ \dfrac{SoC_i - SoC_{ave}}{\Delta SoC_{min}}, & \Delta SoC_{min} \le \left|SoC_i - SoC_{ave}\right| < \Delta SoC_{max} \\ 0, & \left|SoC_i - SoC_{ave}\right| \ge \Delta SoC_{max} \end{cases} \tag{21}$$

where ΔSoC_{min} is minimum SoC deviation, ΔSoC_{max} is maximum SoC deviation, and SoC_{ave} is average value of total battery SoC

$$SoC_{ave} = \frac{1}{n} \sum_{i=1}^{n} SoC_i\ . \tag{22}$$

The optimal power-sharing control with efficiency improvement and SoC balance can be established as

$$V_i = V_{ref} - R_{di} i_{oi} \tag{23}$$

where

$$R_{di} = (1-\tau)\alpha_i \left(\frac{i_{oi}}{C_i R_{linei}}\right) + \tau\left(2a_i i_{oi} + b_i\right) \tag{24}$$

$$\tau = \begin{cases} 0, & \prod_{i=1}^{n} a_i < 1 \\ 1, & \prod_{i=1}^{n} a_i \ge 1 \end{cases}. \tag{25}$$

To achieve the optimal power-sharing effect while controlling the bus voltage in the desired range, introduce β as voltage regulation factor. The proposed optimal droop control with bus voltage constraints is established as

$$V_i = V_{ref} - \beta R_{di} i_{oi} \tag{26}$$

where ΔV_{max} is the max bus voltage deviation and the voltage regulation factor is

$$\beta = \begin{cases} \dfrac{\Delta V_{max}}{\left[\dfrac{i_{oi\_rated}}{C_i} \Big/ \left(R_{linei} + \dfrac{1}{R_{linei}}\right)\right] i_{oi\_rated} + i_{oi\_rated} R_{linei}}, & i_{oi\_rated} < \dfrac{b_i}{\left[\left(1/C_i R_{linei}\right) - 2a_i\right]} \\ \dfrac{\Delta V_{max}}{2a_i i_{oi\_rated}^2 + b_i i_{oi\_rated} + i_{oi\_rated} R_{linei}}, & i_{oi\_rated} \ge \dfrac{b_i}{\left[\left(1/C_i R_{linei}\right) - 2a_i\right]} \end{cases} \tag{27}$$

IV. Real-Time Simulation Verification

In this section, the effectiveness of the proposed strategy is validated through real-time simulation in RT-Lab OP5700. The real-time simulation platform is shown in Fig. 3. The system parameters are shown in Table I.

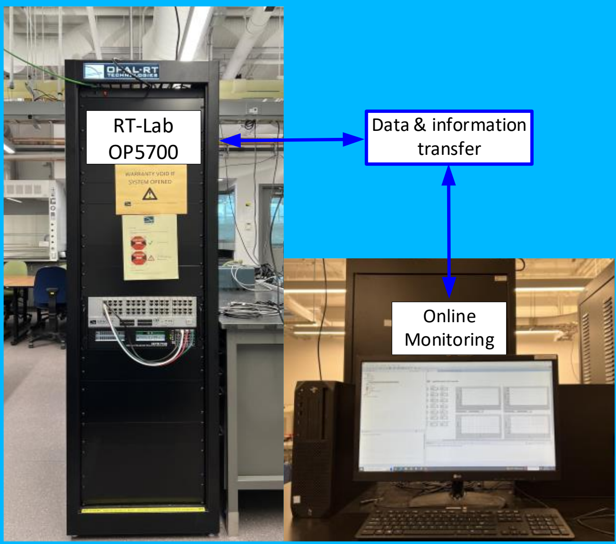

Fig. 3. Real-time simulation platform.

TABLE I
System Parameters

Parameters	Value
Bus voltage /V	400
Bus voltage maximum deviation /V	5
Line resistance /Ω	1
Battery rated voltage /V	150
Battery 1 initial SoC /%	95
Battery 2 initial SoC /%	90
Battery 3 initial SoC /%	85
Maximum SoC deviation /%	3
Minimum SoC deviation /%	1
Converter rated capacity/W	500
Converter inductance/mH	10.5
Converter IGBT switching frequency /kHz	20
Converter 1 loss coefficient	a1=7.293e-04 b1=-0.1963 c1=37.59
Converter 2 loss coefficient	a2=6.293e-04 b2=-0.2218 c2=36.47
Converter 3 loss coefficient	a3=5.293e-04 b3=-0.2375 c3=33.47

To validate the proposed control strategy, the system load is specified as 900W, which is 60% of the rated system load. The paralleled ESUs first conduct the proposed optimal operation strategy. Then, the paralleled ESUs execute the SoC balance strategy proposed in [8] under the same condition.

The total efficiency of the paralleled ESUs under the proposed control strategy and SoC balance strategy proposed in [8] are shown in Fig. 4 and Fig. 5. It can be seen from Fig. 4 and Fig. 5 that under the proposed control strategy, the efficiency of paralleled ESUs improve 0.92% in efficiency operation period and 0.69% in average.

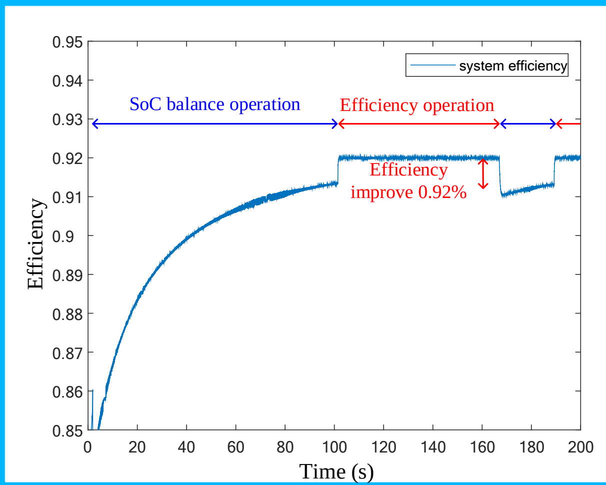

Fig. 4. The efficiency of paralleled ESUs under the proposed control strategy.

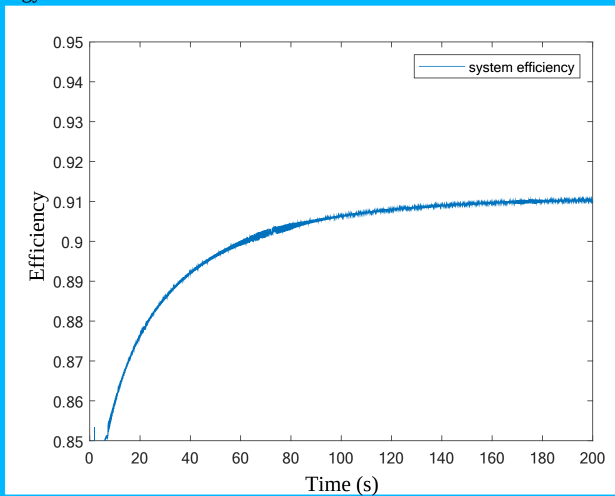

Fig. 5. The efficiency of paralleled ESUs under control strategy in [8].

The SoC of the paralleled ESUs under the proposed control strategy and SoC balance strategy proposed in [8] are shown in Fig. 6 and Fig. 7. It can be seen from Fig. 6 that under the proposed control, the SoC of paralleled ESUs can be controlled in the desired range between 1% and 3%. Under the control strategy proposed in [8], the SoC will be controlled to the same value.

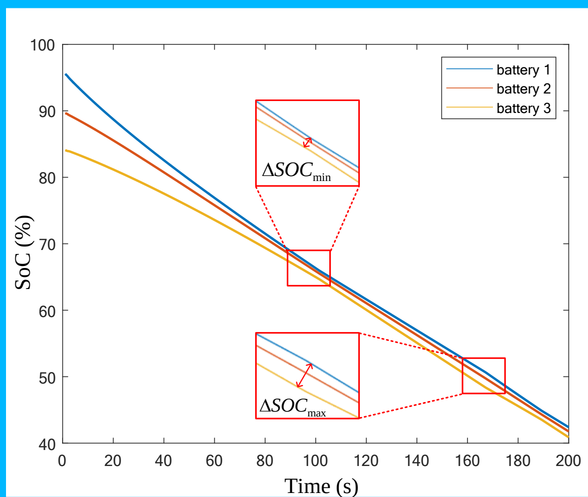

Fig. 6. The SoC of paralleled ESUs under the proposed control strategy.

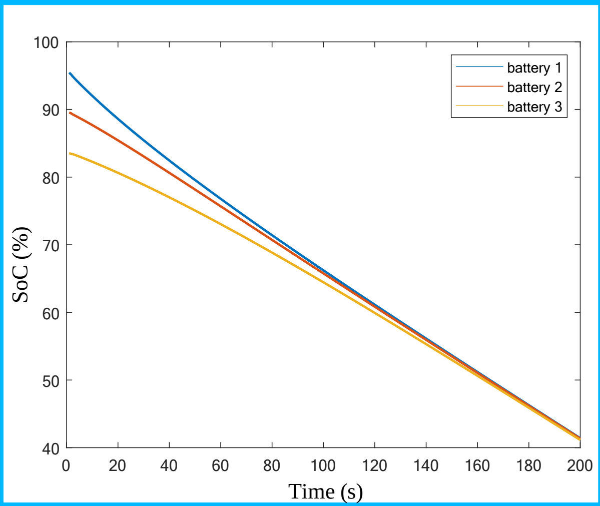

Fig. 7. The SoC of paralleled ESUs under control strategy in [8].

The output current of the paralleled ESUs under the proposed control strategy and SoC balance strategy proposed in [8] are shown in Fig. 8 and Fig. 9.

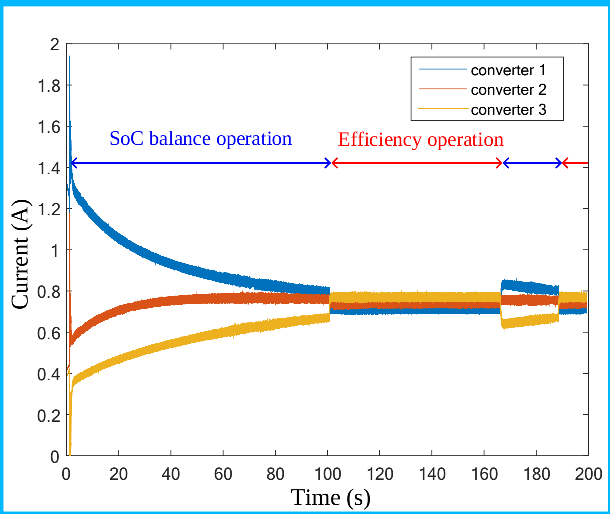

Fig. 8. The power-sharing of the paralleled ESUs under the proposed control strategy.

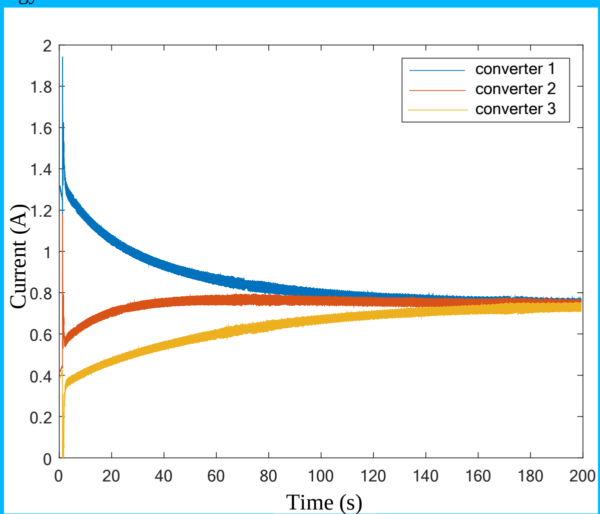

Fig. 9. The Power-sharing of the paralleled ESUs under the control strategy in [8].

The bus voltage under the proposed control strategy and strategy proposed in [8] are shown in Fig.10 and Fig.11. It can be seen from Fig. 10 that the bus voltage is controlled in the desired range during the control parameters actively change progress.

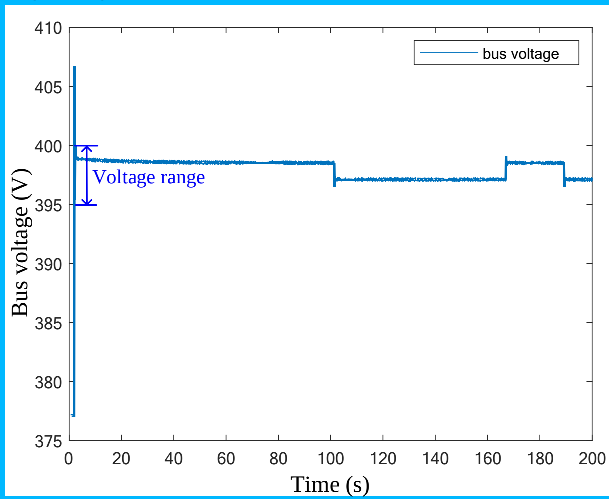

Fig. 10. The bus voltage under the proposed control strategy.

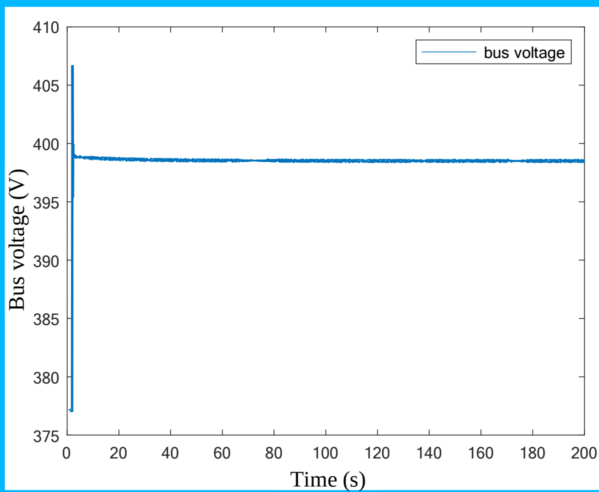

Fig. 11. The bus voltage under the control strategy in [8].

It can be concluded, from the comparison of the proposed control strategy and the SoC balance control strategy in [8], that the proposed control strategy can improve efficiency of paralleled ESUs. Furthermore, the SoC deviation can be controlled in the desired range. The system performance can be enhanced.

V. Conclusions

This paper presents an optimal operation strategy for paralleled ESUs to achieve SoC balance with efficiency improvement. The model is developed considering converter characteristics and the effect of line resistance. The SoC balance operation point is derived by applying Coulomb Counting method. Then, the optimal efficiency operation point for paralleled ESUs is derived by applying Lagrange Multiplier method considering converter efficiency. Based on it, optimal operation strategy is proposed by adjusting operation points adaptively according to paralleled ESUs operation status. Real-time simulation verification is implemented to validate the proposed optimal operation strategy. The verification results show that the proposed control strategy can improve system efficiency by 0.69% on average. Meanwhile, the deviation of SoC is controlled in the desired range between 1% and 3%. The performance of paralleled ESUs is enhanced.

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VII. Biographies

Xiangchen Zhu (Student Member, IEEE) received the B.S. degree in electrical engineering and automation from the Shanghai University of Engineering Science, in 2017. He received the master's degree in mechanical electronics with joint supervision of Shanghai University of Electrical Power and Shanghai University of Engineering Science in 2021. He is currently pursuing the Ph. D. degree from the energy department, Aalborg University. His research interests include the microgrid optimal operation, power electronic power system reliability enhancement, and data-based intelligent power electronic control.

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