SoC Balancing of Different Energy Storage Systems in DC Microgrids Using Modified Droop Control

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***Abstract*—Droop control as a well known approach is used as the basis of the power sharing among different paralleled voltage sources and battery energy storage systems (BESS). In order to extend the lifetime of BESS and avoid the overuse of a certain battery, the State of the Charge (SoC) of BESS should be balanced. This paper reviews and compares three different droop control methods in an islanded DC microgrid that are based on balancing the SoC of different BESS. All of the presented methods are compared together and the best one is selected. The feasibility of the selected method is verified through computer simulations in MATLAB/Simulink for a DC microgrid consisting of three BESS, PV (Photovoltaic) arrays and DC load.**

***Index Terms*—DC microgrid, Droop Control, Battery Energy Storage System, State of Charge Balancing**

I. Introduction

Microgrid is described as a grid that contains generation part and consumption part. The generation part is comprised of grid-tied converter, distributed generations, and battery energy storage systems (BESS). According to the type of sources in generation part, microgrids are defined as AC microgrids or DC microgrids. As the generation sources contain more and more modern DC components, such as photovoltaic panels and batteries and the loads are changing from AC type to DC type, DC microgrid is gaining more and more interests [1] - [2].

Renewable resources like PV (Phtovoltaic) cells generate DC power. On the other hand, a large number of loads use DC voltage [3]. There is a possibility to remove the expensive power converters and connect DC loads to the DC sources. There are different methods for controlling DC sources such as fuel cell power units [4]. These converters are connected to the DC bus via DC/DC converters. There are also some configuration for such DC/DC converters for photovoltaic arrays connected to a DC microgrid [5]. Moreover, DC loads such as motors can be connected to DC microgrid through AC/DC converter. The control algorithm for motors in grid-tied systems has been addressed in [6].

The BESS consisting of the battery and its controllers is an unavoidable part of a DC microgrid. The first reason is that for obtaining a redundant system, there is need for two or more batteries to operate as the back up sources. Thus, they should be controlled to operate autonomously in the system [7]. Second, the nature of renewable resources which are used in DC microgrids is stochastic and there is uncertainty in the system. These uncertainties should be taken into consideration in distributed generation placement for optimizing their generations and total costs of system [8]. To analyze the performance of the system with uncertainties, [9] uses reachability analysis for the grid-tied inverter which can be performed on the state space model of the system.

One of the challenges in DC microgrids is to utilize a control algorithm that ensures stable power balance between generation sources and consumption part. The challenge that comes in paralleling the resources, is the amount of power each of them should produce or absorb. To address this issue, different droop control method has been proposed [10].

Droop control method is a well-known method in microgrids, where the voltages of sources are defined from a voltage reference and droop coefficient. In a microgrid with parallel sources, the power each source produces would be proportional to its droop coefficient. There are different droop control methods proposed for controlling DC microgrids [11]. Most of them do not take SoC of BESS into consideration. For instance, in [11], the objective is power balancing among parallel sources in the DC microgrid.

However, when more than one energy storage unit is connected to a DC microgrid, some of them might be exposed to deep-discharging or overcharging if there is no control over SoC of BESS to be balanced [7].

It is desirable that, in the discharging operation mode, the BESS with higher SoC provides more power and accordingly, in the charging operation mode, the BESS with lower SoC absorbs more current than the others. Therefore, some of the recent works change the droop coefficient in the droop controller according to the SoC of batteries [3] - [12].

In [3], a new droop control method is proposed that can be added to the control algorithm to balance the SoC of BESS. In this approach, the SoC of a BESS is divided by the average of SoCs of other batteries and affects droop coefficient. Thus, there is need for communication between batteries in order to obtain the average of the SoCs.

There is another method for the SoC of each BESS to be balanced and the injected/output power to be equalized. In [13], the droop coefficient is considered to be the original droop coefficient multiplied by the n^{th} order of the SoC. In this reference, it has been shown that in the charging process, the BESS with higher SoC absorbs less power, while the one with lower SoC absorbs more power. Hence, SoC balancing can be gradually obtained. This method does not depend on other batteries information and there is no need for communications or central controller.

Another droop control based SoC balancing method has been proposed in [14] to achieve SoC balancing of BESS with different capacities. The advantageous of this method is that

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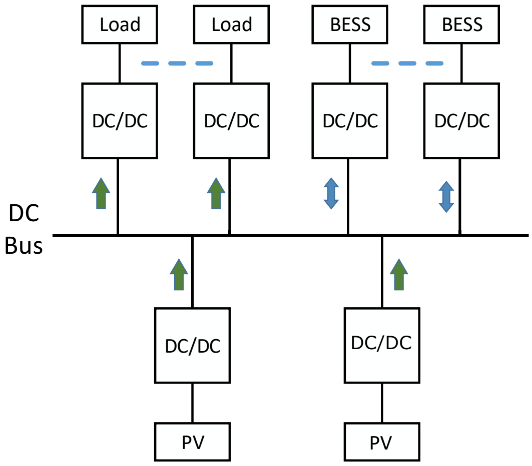


Fig. 1: Schematic diagram of a simple DC microgrid.

the batteries can be considered having different capacities and their injected/output powers are being equalized.
The contribution of this paper is that it compares three different methods of SoC balancing and selects one of them as the basis for performing simulation analysis. The paper is organized as follows. In Section II, the principle of autonomous operation of DC microgrids is presented. Then, different droop-based control strategies are described in Section III. In Section IV, one of the presented methods is selected and the theory behind it, is completely described. Then in Section V, the model is simulated in MATLAB/Simulink and the results are shown. Finally, in Section VI an extension for the presented method is proposed to take the capacities of BESS into consideration. Section VII concludes the overall paper.

II. Operation Principle of DC Microgrids with Paralleled Voltage Sources

Fig. 1 shows the schematic of a typical DC microgrid consisting of BESS and PV panels as the voltage sources of the system and DC loads. As it can be seen from this schematic, all of the voltage sources are considered to be DC type parallel on the DC bus and shall contain droop and voltage controllers to achieve stability.
By considering different droop coefficients for paralleled voltage sources, the power can be shared among them according to their droop coefficients and the BESS produce or absorb power based on their droop coefficients.
During the operation of microgrid, it is necessary to balance the SoC of each BESS in order to avoid over use of a certain battery. Hence, the over charging and deep discharging of a battery can be avoided and the lifetime of the energy storage system is prolonged.
In particular, in the charging process, the BESS with lower SoC shall absorb more power and have lower droop coefficient. However, in the discharging process, this procedure should be changed and the BESS with higher SoC shall have lower droop coefficient.
Beside droop controller, there shall be inner voltage and current control layers to ensure stability. More control algorithms have been addressed by authors of [15] for battery use in the DC power distribution system. By changing droop coefficient, the amount of current the converter produces or absorbs will change. Therefore by modifying this slope, we can make batteries charge/discharge more or less.
For all of batteries, SoC shows what percentage of the capacity of battery is used. This coefficient can be defined as follows:

$$SoC_i = SoC_i(0) - \frac{1}{C_{ei}} \int I_i(t)dt \tag{1}$$

In this equation, $SoC_i(0)$ is the initial SoC of i^{th} battery, C_{ei} is the capacity of i^{th} battery in As and $I_i(t)$ is the output current of the battery.
Hence, the droop coefficients for paralleled BESS shall be modified according to their SoCs. The control objective of this modification is to keep the SoC of all BESS at the same level. By obtaining this objective, the SoC of BESS will converge.
As mentioned in the previous section, different researches have been done in this area. In the following section, three of these different methods are discussed and compared together and the best one is selected as the basis for the simulation analysis.

III. Different Droop Control Methods

In order to balance the SoC of batteries in a DC microgrid, the BESS with more SoC should discharge faster than the others. This idea shall be also applied for the charging operation mode of BESS with different initial SoCs. Different methods for the modification of droop coefficients based on the SoC of BESS are discussed as following.
Case 1: In this method, [3], the droop coefficient is modified as following for the discharging and charging operation modes, respectively.

$$R_{d_i}^{new} = \frac{R_{d_i}}{\beta_i} \tag{2}$$

$$R_{d_i}^{new} = R_{d_i} * \beta_i \tag{3}$$

where, $R_{d_i}^{new}$ is the modified droop coefficient, R_{d_i} is the initial droop coefficient and β_i is defined as

$$\beta_i = \frac{SoC_i}{\frac{1}{n}\sum_{k=1} SoC_k} \tag{4}$$

where, SoC_i corresponds to the SoC of i^{th} BESS.
It can be seen from the equation that if the SoC of a battery is greater than the average of the SoCs, β would be greater than 1 and if the SoC is less than the average of SoCs, it would be less than 1. Thus, in the discharging process, the BESS with higher SoC would have smaller droop coefficient which results in higher discharging current.
Case 2: According to Eq. 1, the SoC balancing of different BESS will be affected by $SoC_i(0)$, $I_i(t)$ and C_{ei} [14]. In order to achieve SoC balancing of BESS with different capacities, a droop-based SoC balancing method has been proposed as following

$$R_d^{new} = \frac{R_d}{c_e}(1 - K_{SoC}SoC_i) \tag{5}$$

In this equation, K_{SoC} is a factor that can be selected to change the amount of modification. From the above equation, it can be seen that the more the SoC, the less new droop coefficient becomes and then, the more discharging current would be.

This method is different from other methods in the case that it takes the capacities of BESS into consideration. It can be noticed that the droop modification is operating correctly for BESS with different capacities. If a BESS has more capacity than the other BESS, then it should discharge more than the others and this fact can be derived from the above equation. The more the capacity is, the less the droop coefficient will be and thus, the battery produces more current.

The droop control method proposed in this reference is just for the discharging operation mode. However, the droop modification can be obtained for the charging operation mode by some minor changes in the formula.

Case 3: In [13], a new droop control method of SoC balancing has been proposed. In this method, for the charging operation mode, the droop coefficient is set to

$$m_i = m_c * SoC_i^n \tag{6}$$

And in the discharging operation mode, the droop coefficient is set to

$$m_i = \frac{m_d}{SoC_i^n} \tag{7}$$

where, m_c and m_d are the droop coefficients for the charging and discharging operation mode, respectively. n is the exponent of SoC, which is utilized to regulate the speed of SoC balancing.

All of these methods have a reasonable results for SoC balancing of BESS. However, the method proposed in [13] has some advantageous over the other two methods and thus, this method is selected to be discussed more in the rest of this paper.

The reasons for selecting this method are summarized as following:

- No need for communication between BESS and easy to be implemented.
- Higher speed of convergence.
- Well presented in [13], both in theory and in computer simulations.
- More focused on SoC balancing of BESS rather than the control algorithms of DC microgrid that are the focus of other references.
- Considering droop coefficients for both charging and discharging operation modes.
- Considering DC microgrids for simulation.

IV. Principle of SoC-Based Droop Control Method

In order to have SoCs of BESS become balanced in discharging and charging operation modes, we can make use of droop coefficient in the droop controller. The part of the droop controller curve in the first quadrant corresponds to the discharging process, and the second quadrant corresponds to the charging process.

First step in checking the feasibility of the method in the convergence of powers and SoCs of BESS is to write the droop control equation as the relation between V_i and P_{oi}:

$$V_i = V_{ref} - m_i * P_{oi} \tag{8}$$

where, V_{ref} is the set point voltage and V_i is the output DC voltage. Considering that the ideal PI voltage controller is used, the DC output voltage of different voltage sources are equal to each other.

Thus, the above equation for all of the BESS in the DC microgrid can be combined together and rewritten as

$$m_1 * P_{o1} = m_2 * P_{o2} = \cdots = m_k * P_{ok} \tag{9}$$

where, k is the total number of paralleled BESS in the DC microgrid.

By considering the modified droop coefficients from Eq. 6 and 7, and replace them in the above equation, we can find the relation between P_{ok} and SoC_k as following.

For the charging operation mode:

$$P_{o1} \sim \frac{1}{SoC_1^n} \ldots P_{ok} \sim \frac{1}{SoC_k^n} \tag{10}$$

For the discharging operation mode:

$$P_{o1} \sim SoC_1^n \ldots P_{ok} \sim SoC_k^n \tag{11}$$

It is concluded from above equation that in the charging operation mode, if SoC_i is greater than SoC_j, then absolute value of the absorbed power P_{oi} is lower than P_{oj}. It means that the SoC_i increases with lower speed than SoC_j. Hence, SoC_i and SoC_j are gradually balanced. This analysis is also applicable for the discharging operation mode.

In order to show this relation, P_{oi} should be just written based on the SoCs of BESS. For this purpose, the net required power which is distributed among BESS according to their droop coefficients is defined as

$$P_{req} = P_{load} - P_{source} = \sum_{k=1}^{n} P_{ok} \tag{12}$$

where, P_{source} is the total power supplied by the sources and P_{load} is the total power required by the loads.

By combining Eq. 12 with Eq. **??** and the fact that P_{oi} are related to the SoC of BESS according to Eq. 11, it yields that for the charging operation mode

$$SoC_i = SoC_{i0} - \frac{P_{req}}{C_{ei}V_{oi}} \int \frac{\frac{1}{SoC_i^n}}{\sum_{i=1}^{k} \frac{1}{SoC_i^n}} dt \tag{13}$$

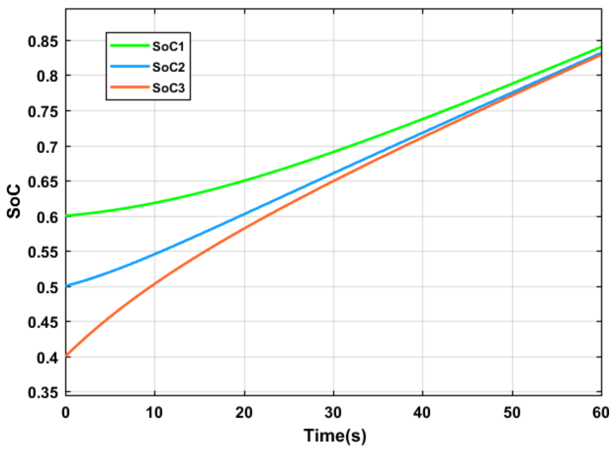
And for the discharging operation mode

$$SoC_i = SoC_{i0} - \frac{P_{req}}{C_{ei}V_{oi}} \int \frac{SoC_i^n}{\sum_{i=1}^{k} SoC_i^n} dt \tag{14}$$

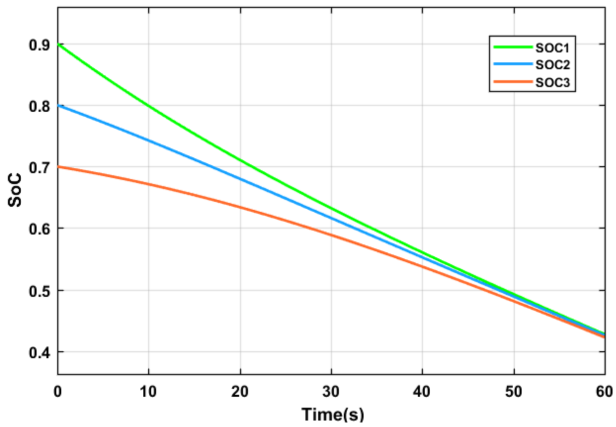
In order to show the convergence of SoC of BESS, a simple DC microgrid consisting of three BESS is considered as an example. The system parameters are shown in Table I. In this table, the first value for the initial SoC of BESS is for the charging process and the second value is for the discharging

TABLE I: System parameters.

Item	Symbol	Value
Initial SoC of First BESS	SoC_{01}	0.6/0.9
Initial SoC of Second BESS	SoC_{02}	0.5/0.8
Initial SoC of Third BESS	SoC_{03}	0.4/0.7
DC Voltage	V_o	600V
Total input/output power	P_{req}	-3/3 kW
Max power rating of converter	P_{max}	2.5 kW



(a) Charging operation mode.



(b) Discharging operation mode.

Fig. 2: Numeric solution of the Eq. 13 and 14.

process.
The exponent n is selected as 6. The selection of this coefficient will be discussed in following sections. By numerically solving the equation for SoC in the charging operation mode and discharging operation mode, Fig. 2 is obtained. From this figure, it is seen that the SoCs of BESS become gradually equal.

A. Stability analysis

The stability analysis can be obtained by observing the eigenvalues of the characteristic equation. There are some other methods for other stability analysis such as transient stability analysis. The algorithm for transient study has been discussed in [16]. The focus of this paper is on the stability analysis of the system. In order to find the linearized characteristic equation, we should utilize small signal analysis, since the original equation is a non-linear one.
The first equation that should be linearized is the droop control equation. The small signal model of this equation is found by perturbing:

$$\hat{V_i} = -m_c SoC_i^n \hat{P_i} - m_c.n.SoC_i^{n-1} P_i \hat{SoC_i} \tag{15}$$

Second equation to be perturbed is the formula for SoC:

$$\hat{SoC_i} = -\frac{\hat{P_i}}{sC_{ei}V_{oi}} \tag{16}$$

In the above equation we suppose that P_i is the output of the low pass filter. Thus, the parameters for the low pass filter is no longer needed to be considered in the equation.
Now, the two small signal equations shall be combined together to remove the perturbed item of SoC.

$$\hat{P_i} = -\frac{sC_{ei}V_{oi}}{m_c SoC_i^{n-1}(nP_i - sC_{ei}V_{oi}SoC_i)}\hat{V_i} \tag{17}$$

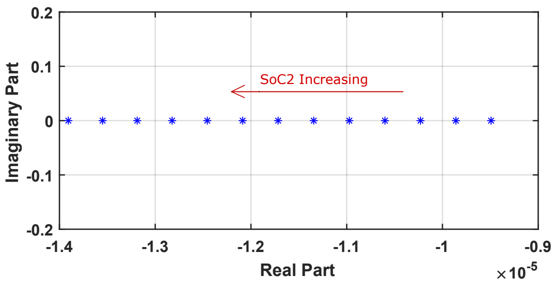
For the characteristic equation, all of the coefficients should be based on $\hat{V_i}$. Thus, we should remove $\hat{P_i}$ and write it based on $\hat{V_i}$. For this purpose, we can use the load side kirchoff's law.

$$P_{load} = \frac{V_i^2}{R_{load}} \rightarrow \hat{P_{load}} = \frac{2V_i\hat{V_i}}{R_{load}} \tag{18}$$

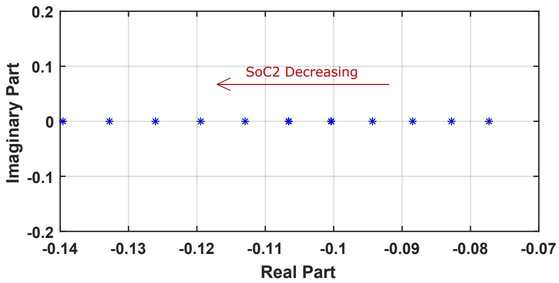
Taking into account the fact that the total amount of power delivered to the load is equal to the power BESS produce, the characteristic equation can be obtained by removing $\hat{V_i}$ on both sides.
Now by considering the system with three BESS as an example, the following form of equation is obtained:

$$A_c s^3 + B_c s^2 + C_c s + D_c = 0 \tag{19}$$

The coefficients in the above equation can be simply found from small signal equations. Also, the same procedure can be applied for the discharging operation mode and the coefficients can be found.
As the eigenvalues of the system are the poles of the characteristic equation, we can analyze the stability of the system by observing the characteristic equations of the charging and discharging operation modes.
In order to show the stability of the system from the derived characteristic equation, two BESS is considered with SoC_1 to be constant while SoC_2 varies. For the variation of SoC_2, the dominant poles of the system are demonstrated in Fig. 3. It is found that all dominant poles of the system locates in the left half of the s domain as SoC_2 varies, which indicates that the system is stable for all SoC_2 variations both for the charging process and discharging process.



(a) Charging Process



(b) Discharging Process

Fig. 3: Dominant pole of the small signal model for the variation of SoC_2.

B. Speed test for the choice of n

As mentioned earlier, n is a parameter which can be tuned to achieve the required speed regulation of SoC balancing and convergence of the output/input power.
In order to observe the speed of convergence, the following variable is defined as follows:

$$e_{SoC} = max\{SoC_i\} - min\{SoC_i\} \tag{20}$$

for $i = 1, 2, ..., k$.
Thus, in order to find the error between SoCs which is directly related to the speed of convergence, we consider a DC microgrid with three BESS. For different amounts of n, the error between SoCs for the discharging operation mode is demonstrated in Fig. 4.
It can be said that if the larger exponent n is selected, the final error between SoCs can be lower. Then, we can see that the speed of SoC balancing increases.

V. Simulation Results

A DC microgrid consisting of three BESS and a constant current source/sink is simulated in MATLAB/Simulink to evaluate the feasibility of the presented method. Different cases are simulated and the results are shown in the following subsections.

A. Case 1: Switching the status of operation from charging to discharging mode.

In this section, the transferring between charging and discharging operation mode is discussed and simulated.
In Fig. 5a, the BESS first operate in discharging operation

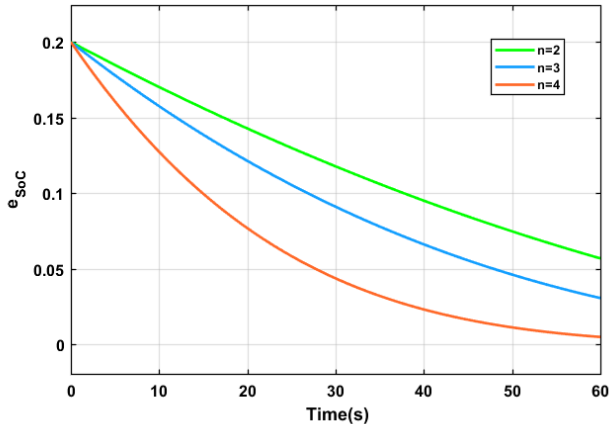
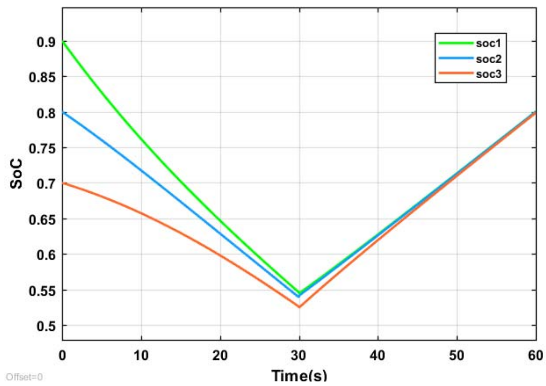
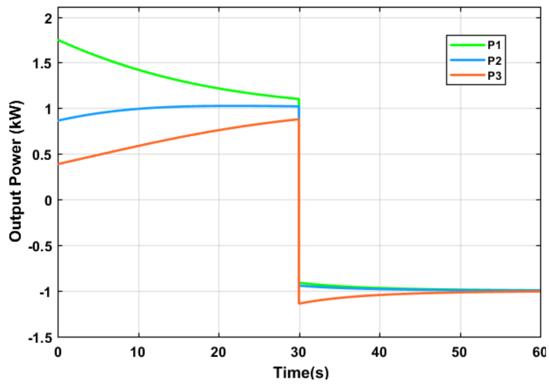


Fig. 4: Difference between SoCs for different exponent n.



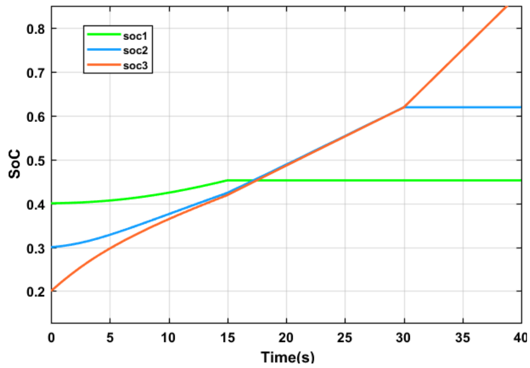
(a) Wave forms of SoCs.



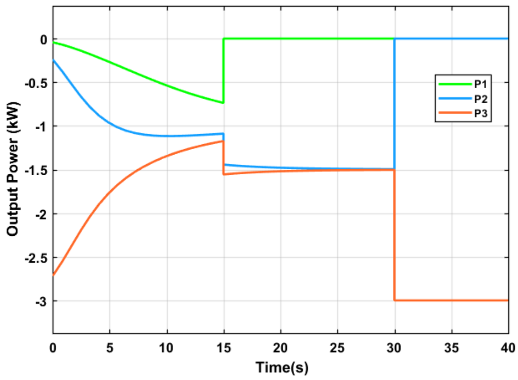
(b) Wave forms of injected/output powers.

Fig. 5: Mode transferring from discharging to charging operation.

mode. Then, their operation is changed to charging mode. The distribution of power among these BESS is also shown in Fig. 5b. As it can be seen, the powers converge totally after the end of simulation time.
The same results can be obtained for the case that BESS first operate in the charging mode, and then switch to discharging operation mode.



(a) Wave forms of SoCs.



(b) Wave forms of absorbed powers.

Fig. 6: Charging process with disconnection of BESS1 and BESS2.

TABLE II: Comparison Between Different Methods

Method	Case1	Case2	Case3
Easy to be implemented	Hard	Easy	Easy
Need for communication	Yes	No	No
Speed of convergence	180s	160s	150s
Capacity included	No	Yes	No

B. Case 2: Disconnection of BESS.

In this case, one of the BESS is disconnected. We want to see the dynamic response of the other BESS in the network. At first, as shown in Fig. 6, all of the BESS operate in the charging mode and the SoCs are gradually converged. At $t = 15s$, first battery is being disconnected, while other BESS continue absorbing power. Then, at $t = 30s$, second battery is begin disconnected and only third battery remains working and continues absorbing power. It can be seen that the system keeps stable and the SoCs become almost balanced before the disconnection. The summary of mentioned methods of SoC balancing is written in Table II. four different criteria are considered for the comparison. Based on this table, It can be seen that third case which has been selected among two others has highest speed of convergence and has no need for communication between sources in the system. Therefore, its implementation is much easier that others.

VI. Conclusion

In this paper, a method of SoC balancing is discussed and simulated. The presented method is selected among three different SoC balancing droop control methods, because it is completely studied for different operation modes and has high speed of convergence.
It has been shown that with the selected method, the SoC balancing is achieved for different case studies. The presented method is simulated in MATLAB/Simulink and the results show its effectiveness in SoC balancing and power equalization.

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