Battery State of Charge Management by Voltage Feedback Modification

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***Abstract*—Due to increase in utilization of DC loads and renewable resources which mostly produce DC powers, there has been an increasing popularity in DC microgrids. In the previous research studies, the focus is more on power balancing among parallel voltage sources of the system while balancing the State of Charge (SoC) of batteries has been overlooked. In this paper, by modifying droop control method as the basis of power sharing in the DC microgrid, the objective of SoC equalization can be achieved. DC bus voltage scheduling is the core of modification to keep the batteries SoCs balanced. First, the paper discusses about an existing droop control based SoC balancing method with voltage scheduling. Then, it proposes a new DC bus voltage scheduling to overcome the drawback of the mentioned method. The methods have been simulated in MATLAB/Simulink and a comparison study has been performed.**

***Index Terms*—DC Microgrid, Droop Control Method, State of the Charge (SoC) Balancing, DC Bus Voltage Scheduling**

I. Introduction

Microgrids are categorized as AC microgrids and DC microgrids, according to type of sources connected. Mostly, generation stage is comprised of renewable resources, especially Photovoltaic (PV) arrays and Battery Energy Storage Systems (BESSs). BESSs help renewable resources in power production, specially in their lack of generation period due to their stochastic nature. As PV arrays and BESSs produce DC powers, DC microgrids are gaining attention. [1].

In the DC microgrids utilizing renewable resources, there are lots of stochastic behavior and uncertainties. Hence, BESSs, consisting of battery units and their controllers, are utilized in the generation stage of DC microgrids to ensure power balance. Moreover, to make the system redundant, more than one BESS is required. Thus, controlling more than one battery unit should be done in an integrated form. In a DC microgrid with several generation units, there should also be predictive control to handle the transient response issues [2].

Previous research items emphasized on equal load sharing and power balance using droop control method as a well-known method in paralleling voltage sources [3]. Droop control can obtain scheduled power sharing without any communications. Therefore, droop control method is commonly used in DC microgrids consisting of parallel sources to schedule an arbitrary power sharing among converters. For instance, to achieve power sharing among BESSs with a reasonable accuracy, a droop control method has been proposed in [4].

However, when more than one BESS is utilized in a DC microgrid, there is possibilities that some batteries exposed to deep-discharging or overcharging without any control on their power sharing and droop control algorithm [5]. Therefore, it is necessary to manipulate droop controller based on BESSs State of Charges (SoCs) and dynamically change the power shared between them to keep their SoCs balanced. Thus, droop control method needs to be modified to have more focus on balancing BESSs SoCs besides power sharing.

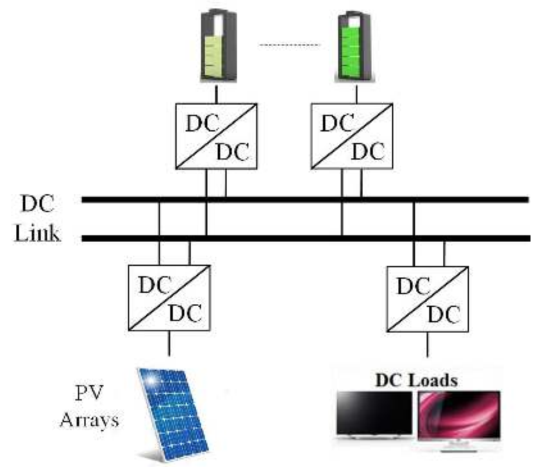


Fig. 1: Schematic diagram of the studied DC microgrid.

For the purpose of balancing the SoC of BESS, it is demanded that the BESS with higher SoC provides more power in the discharging phase, and less power in the charging phase [6]. To address this point, some of recent research studies manipulate droop coefficients by taking BESSs SoCs into consideration [7].

Beside these methods of SoC balancing that change droop coefficients, another control method based on voltage scheduling has been proposed in [8] - [9]. These methods keep the SoCs at the same level, by modifying voltage reference based on BESSs SoCs. In this paper, the method of voltage scheduling presented in [9], has been discussed. Then, a novel method of SoC balancing based on DC bus voltage scheduling is proposed to overcome its drawback.

The paper is organized as following. In Section II, a background of droop control method and BESS SoC is presented. Section III, describes modification of droop functionality by voltage scheduling: one of the existing droop based control

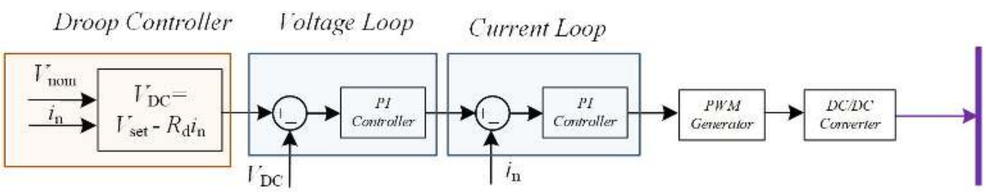


Fig. 2: Control block diagram of a single BESS.

method and the new proposed method. Then in Section V, the methods are simulated in MATLAB/Simulink and compared together. Finally, section VI concludes the overall paper.

II. BACKGROUND

A DC microgrid consisting of Photovoltaic (PV) arrays, BESSs, and loads connected to common DC bus via DC/DC converters is shown in Fig. 1. BESSs are required in all of DC microgrids consisting of PV arrays due to their intermittent nature. They supply and balance required power as PV generated powers vary according to the weather condition and solar irradiance.

PV arrays are connected to DC common bus through DC/DC converters which force them to operate at maximum power point tracking (MPPT). Therefore, they can be considered as current sources to the systems. Loads need to have accurate load control algorithm, in a way that any delays in the control part can be investigated and estimated [10]. In this paper, loads are considered as current sinks. In such situation, BESSs are the only voltage source converters in the system. They regulate the DC bus voltage via their controllers and are considered to work in voltage control mode.

BESSs are connected to DC bus through DC/DC buck converters with droop controllers. Block diagram of a droop controlled BESS and its corresponding controllers is shown in Fig. 2. It is shown that the BESS has PI controllers as voltage and current controllers. Droop controller with parameters of R_d as droop coefficient and V_{nom} as the predefined voltage set point, acts as a secondary level of control.

In the system with uncertain energy resources, there is need for having a robust contorl method [11]. The BESSs voltage and current controllers are considered to be PI controllers and are designed in a way that make BESSs stable under any load fluctuations. The procedure of internal controller design has been addressed by the authors of this paper in the previous works. The droop controller in the secondary level is responsible for power sharing management between BESSs. The droop controller is normally designed statically based on system characteristics. For the purpose of SoC balancing, it should follow a SoC calculator which monitors the SoC of BESS and feeds the droop controller for modifying the droop formula. The traditional droop controller used in many applications of power sharing in microgrids is shown as follows.

$$V_{DC} = V_{set} - R_d I_o \qquad (1)$$

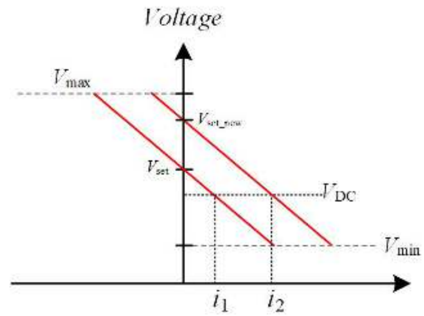


Fig. 3: Modifying droop functionality by changing DC voltage set point.

where, V_{DC} is the DC bus voltage, V_{set} is the DC bus voltage set point, R_d is droop coefficient and I_o is the output current.

It can be seen from above formula that by changing V_{set}, the droop function can be manipulated. Thus, this value can be considered as a parameter depending on SoC of batteries.

The SoC of a battery is formulated as below. It is calculated based on initial SoC, output current and battery capacity [12]. Dimension of batteries can be also formulated in this equation together with the battery capacity.

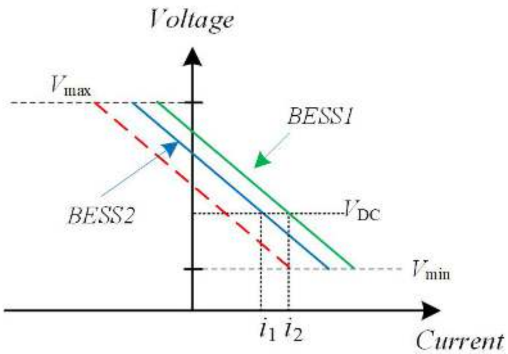
$$SoC = SoC_0 - \frac{1}{C_e}\int I(t)dt \qquad (2)$$

where, SoC_0 is battery initial SoC, C_e is the capacity of the battery and $I(t)$ is the output current.

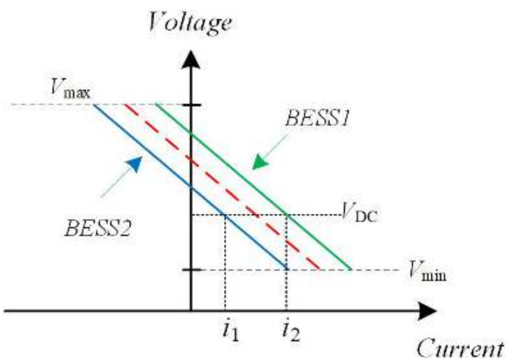
The calculated SoC can be used to manipulate the droop formula by adjusting the DC bus voltage set point. Fig. 3shows that by adjusting the voltage set point V_{set} to V_{set_new}, the curve can be shifted up or down. Then, the corresponding output current can be modified based on the desired output voltage. For instance, by increasing the voltage set point, V_{set}, the droop curve is shifted up and the output current is changed accordingly from I_1 to I_2.

This observation gives us the idea of changing set point according to SoC of batteries. The main objective of this manipulation is to keep the BESSs SoCs equalized and avoid deep discharging or overcharging of a particular battery. This objective can be achieved by forcing BESS with higher SoC produces more current in the discharging phase and absorbs lower current in charging phase.

In the following section, an existing method of SoC balancing with the help of voltage scheduling is discussed and a



(a) Existing Method



(b) Proposed Method

Fig. 4: Droop curve modification for two methods of voltage scheduling.

new control method is proposed to overcome the drawback of the mentioned method.

III. Modification of droop functionality by voltage scheduling

As mentioned in the earlier sections, in a DC microgrid with BESSs as parallel voltage sources, there is need to equalize SoCs. For this purpose, the battery with higher SoC should discharge more and charge less. Therefore, the droop formula should be modified based on this concept. From Eq. 1, it can be seen that there are two main variables that provide the option to change the droop functionality: R_d and V_{set}. In some recent studies, the droop coefficient is changed according to the monitored SoC [13]. In this paper, it is assumed that droop coefficients are the same as the pre-defined value and SoC balancing is achieved based on manipulating DC bus voltage set point, V_{set}. With the voltage scheduling, the output power and corresponding current of a BESS can be controlled dynamically according to change of SoC.

The DC bus voltage calculated from droop formula is based on DC voltage set point and droop coefficient. In one of the existing methods of voltage scheduling [9], a proportional gain of battery SoC is added to the predefined voltage set point. Then, the SoC can be monitored dynamically and the droop functionality can be modified accordingly. The updated formula is shown in the following equation.

$$V_{set}^{new} = V_{set} + (KSoC) \tag{3}$$

According to this equation, by getting feedback from SoC calculator and adding a proportional amount to the predefined set point, the droop curve is shifted up. The amount of shifting depends on the SoC. If a BESS has higher SoC, then its droop curves is shifted up more which results in producing more current in the discharging phase. The same analysis can be done for the charging phase, when PV arrays produce more power than demanded and BESSs are responsible for absorbing extra energy. This idea can be observed in Fig. 4a, where the original droop curve is the red dashed one, and the blue and green curves show the shifted curves for two batteries with different SoCs.

In order to find the best value for the proportional gain of SoC, K, the acceptable voltage range should be taken into consideration. We consider the DC microgrid having the predefined set point of $380V$ and voltage regulation of 5%. Then, the DC microgrid operates in the range of $[360V, 400V]$. Considering the fact that maximum amount of SoC meets the upper range by shifting the curve to the maximum permissible amount, the following equation can be used for defining K.

$$400 = 380 + (K * 1) \quad \rightarrow \quad K = 20 \tag{4}$$

Therefore, by selecting K equal to 20, the DC bus voltage doesn't exceed the limits. The selection of parameter K is totally independent of the number of BESSs in the system and is a factor of desired voltage range.

The main drawback of this method is that it shifts the droop curves up for all of BESSs operating in the system, which means the new DC bus voltage will be higher than the predefined value. However, it is demanded that the DC microgrid operates at the predefined value.

In order to overcome the mentioned drawback of the existing method, a new method of voltage scheduling with the purpose of SoC balancing is proposed.

A. *Proposed Method*

For the purpose of SoC balancing, the following voltage scheduling is proposed to be used as the set point of each BESS droop controller:

$$V_{set}^{new} = V_{set} + K(SoC - SoC_{avg}) \tag{5}$$

where,

$$SoC_{avg} = \frac{\sum_{i=1}^{n} SoC_i}{n} \tag{6}$$

The difference between the proposed method and the existing method is shown in Eq. 5. Based on the difference of a certain BESS SoC from the average of all SoCs, the droop curve can be shifted up or down. This idea is shown in Fig. 4. The red dashed curve shows the droop function with the

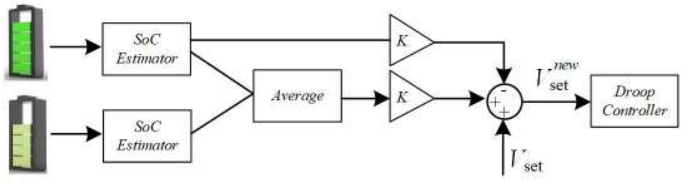


Fig. 5: Block diagram of the proposed droop control method.

predefined values. Then, the curve for the BESS with higher SoC is shifted up, while it is shifted down for the other BESS. It can be seen that the formula is applicable for the case with more than two BESSs as n in Eq. 6 can be any number.

Considering the amount of K as exiting method, it can be seen from Fig. 4 that the set point for BESS with higher SoC is increased, while it is decreased for the BESS with lower SoC, in the discharging mode. The block diagram of the updated droop controller is shown in Fig. 5.

The same analysis can be achieved for the charging mode. The BESS with higher SoC should absorb less power than the other one. This objective can be achieved by increasing the voltage set point and shifting up the droop curve. Then, the absolute value of charging current will become lower, which means the battery absorbs less current.

The proposed method needs more communication between BESSs. Batteries need to share their SoC information with each other. Thus, there is need for a means of communication between BESSs to implement the proposed method.

IV. Simulation Results

To validate the SoC equalization in the two mentioned methods, a DC microgrid consisting of two BESSs, PV arrays working in MPPT mode and constant power load is considered for the simulation. It should be noted that both methods can be applied to larger systems with more than two BESSs.

BESSs are connected to the DC bus via DC/DC buck converters. The specifications of the DC microgrid that is simulated in MATLAB/Simulink, internal PI voltage and current controllers and amounts of output filters are the same as [5]. The predefined set point for the DC bus voltage is $380V$ and the droop coefficients for both batteries are $150/260$. Batteries are considered having the same capacities of 10000 As. It should be noted that for both methods, the PI controller tuning gains, PWM generator and DC/DC buck converters parameters are considered the same. The two methods are compared together based on the speed and time of SoC convergence.

Fig. 6 shows the DC bus voltage for the proposed method. As it can be seen from this figure, the DC voltage is kept constant around $380V$, which is the desired amount.

The two mentioned methods for SoC balancing are simulated and the results are shown in Fig. 7. At the beginning, the BESSs have initial SoCs of 0.8 and 0.6, respectively. We consider PV arrays produce less energy than the demanded power. Therefore, the BESS are working in discharging phase to supply the required power. Results of simulation for the existing method are shown in Fig. 7a, c. These figures show

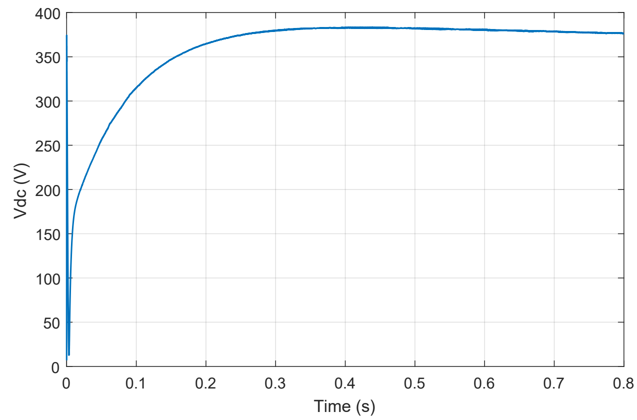


Fig. 6: DC bus voltage.

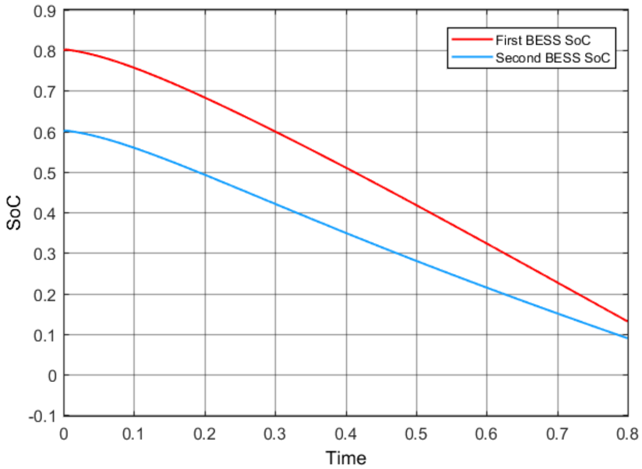
the converter current difference for two BESSs. As the first BESS has higher SoC, the voltage set point becomes higher and the amount of current produced increases. This fact is validated and shown in Fig. 7c. First BESS has higher current with respect to the second BESS.

It can be seen from Fig. 7a that the speed of SoC balancing is low, meaning that by utilizing the existing method, BESS SoCs are converging, but not completely equalized. Results of simulation of the proposed method are shown in Fig. 7b, d. From these two figures, it can be seen that the SoC balancing is achieved with higher speed than the existing method.

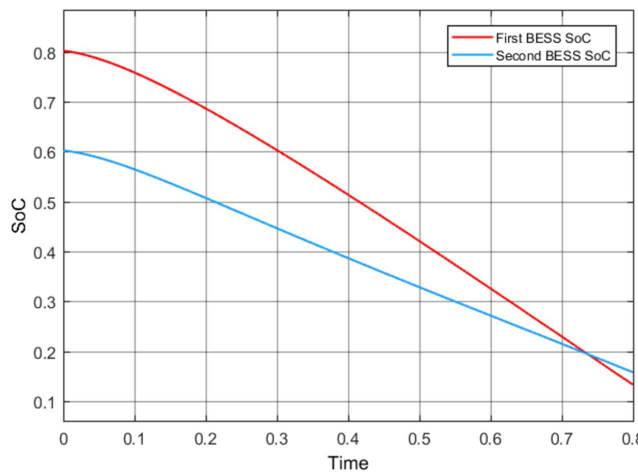
Moreover, it is shown in Fig. 7d that the first BESS current is much higher than the second BESS current. This observation completely validates the basis theory behind the proposed method. First BESS produces more current which results in more reduction in its SoC. Also, after BESSs SoCs are equalized, they are considered the same from the DC bus point of view and so their currents are getting closer at the end of simulation time. It is seen that both methods work fine in satisfying the objective of SoC balancing but with different speed of convergence. Again, the proposed method makes DC bus voltage remain in the desired range. DC bus voltage for the proposed method is kept constant around $380V$, while for the existing method the DC bus voltage would be around $400V$.

V. Conclusion

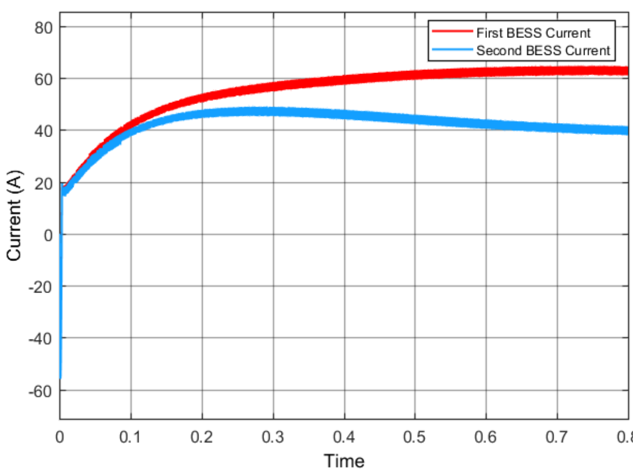
Battery Utilization for compensating the stochastic behavior of renewable resources are gaining popularity. In this paper, a novel control algorithm based on droop control has been proposed to manage batteries and their state of the charges. The basis of control algorithm is on manipulating predefined voltage set point of the droop controller. The proposed method has been compared with the existing one, both operating by modifying voltage set point. The proposed method overcomes the drawback exists in the available method of SoC balancing. Simulation analysis is done in MATLAB/Simulink on a DC microgrid with two batteries. The results demonstrate SoC equalization with higher speed in the proposed method.



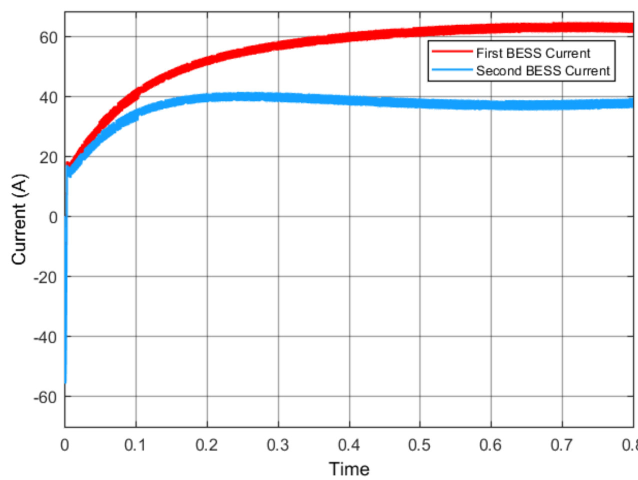
(a) BESSs SoCs for the existing method.



(b) BESSs SoCs for the proposed method.



(c) BESSs Currents for the existing method.



(d) BESSs Currents for the proposed method.

Fig. 7: Results of simulation for two different methods of SoC balancing based on voltage scheduling.

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