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# Novel Droop Control of Battery Energy Storage Systems Based on Battery Degradation Cost in Islanded DC Microgrids

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**ABSTRACT** This paper presents a new droop control method to reduce battery degradation costs in islanded direct current (DC) microgrids for multiple battery energy storage systems (BESSs). BESSs may have varying installation costs and battery cycle life characteristics depending on battery type, energy capacity, and maximum output power. These differences cause different battery degradation costs among BESSs despite exchanging the same amount of energy. To autonomously reduce the total battery degradation cost, an incremental cost (IC) of a BESS is used as a criterion for determining the state-of-charge level of BESSs and is calculated based on the battery cycle life curve containing the battery degradation information. By adopting an IC–voltage droop control, the BESSs can maintain an operating point of equal IC, an optimal point for cost minimization. Subsequently, small-signal stability analysis is performed using the state-space model of the proposed method. The case study validates that the proposed method can reduce the total battery degradation cost with a small-signal stable operation in islanded DC microgrids.

**INDEX TERMS** Battery energy storage system, DC microgrid, degradation cost, droop control, economic operation, incremental cost.

## I. INTRODUCTION

Advances in power electronics have led to increased production of direct current (DC) systems as DC systems have greater energy conversion efficiencies [1]–[4]. At a distribution level, most distributed generators (DGs) such as battery energy storage system (BESS), fuel cells, and renewable energy sources (RES) generate DC power. Many modern loads, such as electric vehicles, lighting, data centers, and air conditioners, require DC power. In other words, both generation and load side interface with DC voltage, allowing the DC system to be an efficient choice by eliminating additional rectification and inversion converter stages [5]. Furthermore, DC systems can reduce the line loss and increase maximum transfer power capacity [6] and have less operation complexity because frequency regulation and reactive power compensation are not required. Owing to these merits, DC

systems, especially DC microgrids, are being increasingly developed.

Among the various facilities in DC microgrids, BESSs play an essential role in reliable and economic operation because they have the capability of energy storage, bidirectional energy exchange, and fast output response [7]. In grid-connected mode, BESSs are usually scheduled to reduce the microgrid operation cost by shifting the time of energy consumption based on the forecasting values (energy arbitrage and peak shaving). On the contrary, in islanded or isolated microgrids, where power balance must be satisfied by its own resources, BESSs should adjust its output power in real time to cope with unpredictable net load variation. Recently, the penetration level of RES such as photovoltaic and wind power is increasing, and they usually adopt the maximum power point tracking for economic purposes. This may cause more instantaneous power fluctuations and even surplus power in the grid; thus, the role of BESSs is becoming more vital.

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The charging and discharging processes of a BESS cause an increase in battery cell impedance and a decrease in battery capacity. This is called battery degradation, which can be affected by various factors such as depth of discharge (DoD), temperature, rate of charge/discharge, dwell time at low and high state-of-charge (SoC), and current ripple [8]. When the degradation accumulates, the battery should be replaced, thereby resulting in maximum allowable charge and discharge cycles [9], [10]. In addition, BESSs still have high installation costs and have time dependency because of the SoC. Thus, a proper control scheme for a BESS should be developed considering the battery degradation cost.

The battery degradation cost has been dealt with for various applications in energy management systems. A linear degradation cost model was adopted for energy coordination (fixed cost coefficient) in [11], [12]. Using the battery cycle life curve, the nonlinear effect of DoD on battery degradation was reflected to set the optimal dispatch in [13]–[16]. A realistic battery degradation cost was formulated considering temperature as well as DoD from the perspective of economics in [17]. In [18], an accurate battery degradation model was trained by deep reinforcement learning for energy arbitrage. However, the above-mentioned methods are aimed to schedule the battery operation over time based on net load forecasting and/or hourly price, which may be difficult to apply for real-time control of islanded microgrid.

Decentralized control is suitable for real-time power balancing in islanded microgrids by using local measurement data [19], [20]. Low cost and high scalability are also the merits of decentralized control. Many studies have attempted to develop decentralized control methods for islanded DC microgrids, and most of them were based on droop control. A basic form of droop control is to use the linear relation of the output voltage and power, and to set the ratio of power sharing proportional to maximum output power [21]. In [22], a BESS assigned its SoC to the output voltage using the SoC–voltage (SoC–V) droop control, and other DGs supported the BESS to keep the scheduled SoC value. Similarly, the BESS operation mode was divided based on the SoC level for SoC management by utilizing DC bus signaling in [23]. Regarding the economic purpose, in [24], the normalized generation cost function is integrated into the droop control to reduce the total generation cost of DGs. In [25], [26], an incremental cost (IC)-based droop control was proposed for autonomous microgrids to achieve equal IC. In [27], the droop settings were adjusted to solve the decentralized economic dispatch problem for lower-layer control which uses only local measurement data. However, most investigations consider only the operation costs of DGs whose cost curve is a function of output power, although the BESS is an essential facility in microgrids.

Control methods for multiple BESSs in islanded microgrids have also been studied in recent years. Most investigations have focused on SoC balancing among the distributed BESSs without communication [28]–[34]. If all BESSs are identical or have the same specifications, SoC balancing

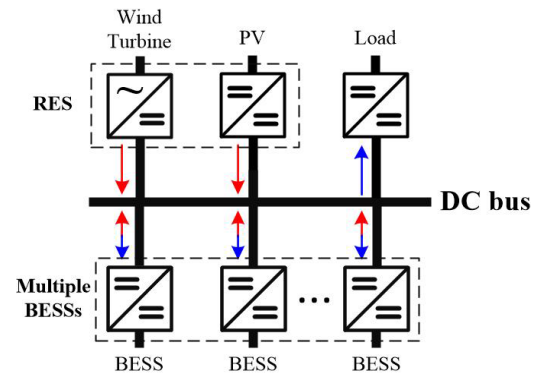


FIGURE 1. Configuration of DC microgrid.

makes the BESSs supply energy simultaneously and prolongs the lifetime of the BESSs. However, accurate SoC balancing of all BESSs is not always the best solution from an economic perspective because BESSs may have different cycle life characteristics and installation costs (different battery degradation cost). If one BESS has a relatively low cost and high cycle life, it would be better to use it more. Therefore, a control method for BESSs that considers the battery degradation cost can improve the economics of an islanded microgrid.

In this paper, a new droop control method for BESSs in islanded DC microgrids is proposed to reduce the total battery degradation cost. This droop control method enables the coordination of multiple BESSs and can determine the steady-state SoC level in a decentralized manner. BESSs may have varying installation costs and battery cycle life characteristics depending on battery type, energy capacity, and maximum output power. Herein, to reflect the different characteristics, an IC of a BESS is newly defined as the criterion for determining steady-state SoC level. The IC of BESS is calculated from the battery cycle life curve, which is a function of the SoC and contains the battery degradation information. Then, the IC–voltage (IC–V) droop control of the BESS is implemented to satisfy the equal IC. Furthermore, small-signal stability analysis is performed using the state-space model of the proposed method, ensuring small-signal stable operation.

The remainder of this paper is organized as follows. Section II presents the background of droop control for BESSs in islanded DC microgrids. Section III describes the proposed droop control based on battery degradation cost for economic operation. In Section IV, small-signal stability of the proposed method is analyzed. Section V shows the simulation results that demonstrate the performance of the proposed method, and Section VI contains concluding remarks.

## II. BACKGROUND

Fig. 1 shows the configuration of a typical DC microgrid consisting of RESs, loads, and multiple BESSs. RESs are usually operated in maximum power point tracking for economic purposes. Thus, they can be regarded as current sources and

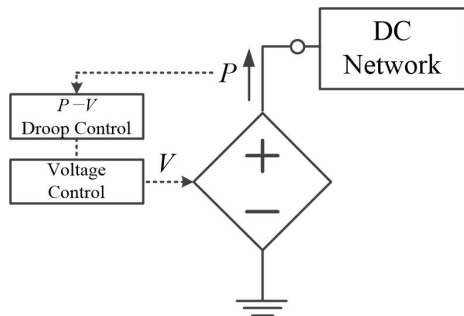


FIGURE 2. Inverter control logic.

negative loads and can be shown in the form of net load with a load demand from the viewpoint of network injected power [34]. As RESs and loads have uncertainty (i.e., unpredictable power output or consumption), BESSs should maintain the power balance in real-time by utilizing their fast response time and bidirectional operation (charge and discharge).

**A. PRINCIPLE OF DROOP CONTROL IN ISLANDED DC MICROGRID**

Droop control is one of the most common methods to cope with load fluctuations and to share output power among distributed energy resources in islanded microgrids. Unlike AC systems where the system frequency and voltage magnitude are usually controlled by the active and reactive power, respectively, DC systems should be controlled only by the relationship between active power and voltage. Fig. 2 shows the simplified inverter control logic of a DC microgrid. To maintain the power balance in an autonomous manner, at least one inverter must act as a voltage source, and its output voltage can be determined from a locally measured output power, such that

$$V_i = V_i^0 + m_{P,i} (P_i^0 - P_{mea,i}), \tag{1}$$

where  $V$  is the voltage,  $P$  is the output power,  $m_P$  is the slope of power–voltage droop, the superscript 0 denotes the set-point, subscript  $i$  denotes the BESS index, and subscript  $mea$  denotes the measured value. After measuring the output power, the output voltage is calculated from (1) generated by adjusting the gate signal at the voltage controller. Fig. 3 shows the basic principle of droop control of two BESSs acting as voltage sources. The initial operating points of the two BESSs are  $A_1$  and  $A_2$ . As the net load increases, the BESSs increase their output power and decrease their output voltage. During this process, the operating points move to  $B_1$  and  $B_2$  on each droop curve. The ratio of  $m_{P,1}$  and  $m_{P,2}$ , which are predetermined, decides the sharing ratio for net load fluctuation, and the absolute values of  $m_{P,1}$  and  $m_{P,2}$  decide the amount of voltage deviation  $\Delta V$ . Because the voltage deviation is equal at two BESSs (it is assumed that the bus voltage difference owing to the line resistance is negligible in small-sized microgrids), the power deviation is inversely proportional to the droop slope  $m_{P,i}$ .

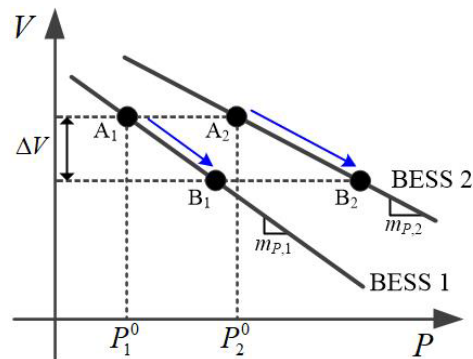


FIGURE 3. Principle of droop control.

**B. DROOP CONTROL OF BATTERY ENERGY STORAGE SYSTEM**

Because the SoC level affects the battery life and charge/discharge capability, it should be managed in the BESS control while maintaining the power balance. The typical objective of management is to maintain the SoC balancing among BESSs. One method to do this is to make the droop slope be a function of SoC. The fundamental principle is that the BESS with a high SoC should also have a high  $m_{P,i}$  during charging and a low  $m_{P,i}$  during discharging (because the power is inversely proportional to  $m_{P,i}$ ). It can be implemented by setting the droop slope to be [29]

$$m_{P,i} = \begin{cases} \alpha_{c,i} SoC_i^n, & \text{charge} \\ \alpha_{d,i}/SoC_i^n, & \text{discharge} \end{cases} \tag{2}$$

where  $\alpha_c$  and  $\alpha_d$  are the droop coefficients for the charging and discharging process, respectively, and  $n$  is the exponent of SoC involved to regulate the speed of SoC balancing [29]. The SoC of a BESS can be estimated by integrating the measured output power, such that

$$SoC_i = SoC_{ini,i} - \frac{1}{E_i} \int P_{mea,i} dt, \tag{3}$$

where  $E$  is the energy capacity of BESS and  $SoC_{ini}$  is the initial SoC. In (2), the droop slope is set proportional to the  $n$ th order of the SoC level during charging and inversely proportional to the  $n$ th order of the current SoC during discharging. By doing so, as the BESSs continue to charge or discharge, even though the initial SoC is different, the SoCs eventually converge to the same value under the same set-points,  $V_i^0$  and  $P_i^0$ .

Another method for balancing the SoC level is to adopt the SoC– $V$  droop control that uses a linear function of output voltage and SoC (not output power) [22]. The output voltage of BESS with SoC– $V$  droop control can be expressed as

$$V_i = V_i^0 - m_{SoC,i} (SoC_i^0 - SoC_i), \tag{4}$$

where  $m_{SoC}$  is the slope of SoC– $V$  droop. By adopting (4), a BESS increases/decreases its output voltage as the SoC increases/decreases. If the droop slope and set-points of all BESSs ( $m_{SoC,i}$ ,  $V_i^0$ , and  $SoC_i^0$ ) are the same, the SoCs will

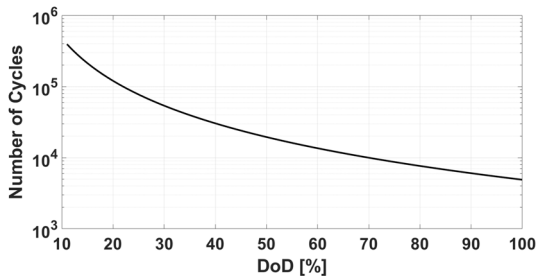


FIGURE 4. Lifetime cycles of a battery versus depth of discharge.

converge to the same value. In both methods, the fundamental principle is that the information of the SoC level is assigned to the grid voltage and thus can be shared among BESSs in a decentralized manner. However, the SoC balancing among the BESSs can efficiently prolong the battery life only if the batteries have the same characteristic. Hence, a control method that can consider each battery characteristic is necessary.

### III. NEW DROOP CONTROL BASED ON BATTERY DEGRADATION COST

Fig. 4 shows a typical curve of battery lifetime cycles versus DoD. The cycle life represents the maximum number of full cycles (recharging after discharging). As the BESS deeply discharges (high DoD), the number of charge and discharge cycles significantly decreases. Because each battery has its own lifetime cycles, even though the same amount of energy is exchanged, it results in different degradation costs. The battery degradation can also be affected by other factors such as temperature, rate of charge/discharge, dwell time at low and high SoC, and current ripple. However, these factors can be handled from an improvement of the converter control and a management of the battery container; thus, only the effect of DoD is discussed herein.

#### A. INCREMENTAL COST OF BATTERY ENERGY STORAGE SYSTEM

To reflect the characteristics of battery cycle life and apply them to the control method, the mathematical expression of the cycle life curve is needed. The cycle life of the battery can be expressed as a function of DoD, such that [8]

$$L_i = \beta_{0,i} \times DoD_i^{-\beta_{1,i}} \times e^{\beta_{2,i}(1-DoD_i)}, \quad (5)$$

where  $\beta_2$ ,  $\beta_1$ , and  $\beta_0$  are the curve-fitting parameters based on the battery type and data provided by the manufacturer. As  $DoD = 1 - SoC$ , one cycle from a full charge to a specific SoC costs a battery capital cost,  $C_{tot}$ , divided by the corresponding total cycles  $L(SoC)$ . Therefore, if the initial SoC is  $SoC_a$ , and it reaches  $SoC_b$  after discharge, the additional degradation cost can be calculated as follows:

$$Degradation\ Cost = \frac{1}{2} \left( \frac{C_{tot}}{L(SoC_b)} - \frac{C_{tot}}{L(SoC_a)} \right). \quad (6)$$

When the degradation cost is calculated in a situation where the BESS discharges and the SoC is reduced, one

full-cycle cost,  $C_{tot}/L(SoC)$ , is divided by two, as shown in (6) (i.e., half-cycle cost). From (6), the IC of the BESS with respect to the energy can be defined and calculated as

$$\begin{aligned} IC_i &= -\frac{C_{tot,i}}{2E_i} \frac{d(1/L_i)}{dSoC_i} \\ &= \frac{C_{tot,i}}{2E_i} \frac{1}{\beta_{0,i}} e^{-\beta_{2,i}SoC_i} \\ &\quad \times \left[ \beta_{1,i}(1-SoC_i)^{\beta_{1,i}-1} + \beta_{2,i}(1-SoC_i)^{\beta_{1,i}} \right]. \quad (7) \end{aligned}$$

From (7), the IC of the BESS is a function of the SoC level and represents the marginal degradation cost change with respect to the energy change (e.g., \$/kWh). Note that (6) and (7) are derived from the discharge mode. However, the IC can be used as an increment of degradation cost even during charging by imaging that time flows in the opposite direction with regard to (7).

#### B. PROPOSED DROOP CONTROL FOR COST MINIMIZATION

Cost minimization is one of the major operational objectives of a system operator. In terms of conventional generation cost minimization, the ICs of all generators not operating at their power limits are equal at the optimal point (i.e., equal IC principle) [36]. This principle can be applied to determine the output of the BESSs because the IC of a BESS is defined by (7) based on the degradation cost. In other words, if the ICs of all BESSs are equal, the total battery degradation cost can be minimized. For this, the new droop control based on the IC of a BESS is as follows:

$$V_i = V^0 + m_{IC} (IC^0 - IC_i), \quad (8)$$

where  $m_{IC}$  is the droop slope of IC-V droop control. In (8),  $V^0$ ,  $m_{IC}$ , and  $IC^0$  are common parameters among BESSs. The principle of achieving equal IC is similar to that of equal SoC (4). The principle of proposed droop control method is shown in Fig. 5, whose left- and right-hand sides are the SoC-IC curve (7) and the IC-V curve (8), respectively. The BESS determines the output voltage based on its IC, which is calculated by the SoC level. Because  $V^0$ ,  $m_{IC}$ , and  $IC^0$  are common parameters and the output voltages should be same in steady-state ( $V_1 = V_2$ ), the ICs also have the same value ( $IC_1 = IC_2$ ). As the BESS discharges continuously, the SoC decreases, thereby increasing the IC. This leads to a decrease in output voltage (the operating point moves along the blue arrow) but still keeps the same IC of BESSs. In other words, the BESSs follow the equal IC points in a decentralized manner by assigning the IC to the voltage.

#### IV. SMALL-SIGNAL STABILITY ANALYSIS

A state-space model of the proposed droop control method is established to investigate the small-signal stability. The state-space model is formulated in terms of deviations of instantaneous voltage and current from the operating point. The first-order low pass filter is used to measure the power for SoC estimation, according to (3), and the cutoff frequency



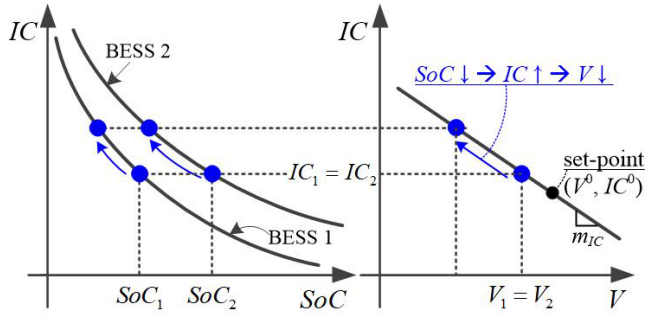


FIGURE 5. Proposed droop control principle for reducing total battery degradation cost.

of all filters is  $\omega_c$ . Subsequently, the measured output power,  $P_{mea,i}$ , can be expressed using instantaneous output voltage and current,  $V_i$  and  $I_i$ , as

$$P_{mea,i} = \frac{\omega_c}{s + \omega_c} V_i I_i. \quad (9)$$

From (3) and (7)–(9), the deviation in output voltage of a BESS can be expressed as

$$\Delta V_i = -m_{IC} \Delta I C_i, \quad (10)$$

where

$$\begin{aligned} \Delta I C_i &= -\frac{1}{E_i} \times \frac{dI C_i}{dSoC_i} \times \frac{\Delta P_{mea,i}}{s} \\ &= -\frac{1}{E_i} \times \frac{dI C_i}{dSoC_i} \times \frac{\omega_c}{s(s + \omega_c)} \left( V_i^{(0)} \Delta I_i + I_i^{(0)} \Delta V_i \right), \end{aligned} \quad (11)$$

$$\begin{aligned} \frac{dI C_i}{dSoC_i} &= -\frac{C_{tot,i}}{2E_i} \frac{1}{\beta_{0,i}} e^{-\beta_{2,i} SoC_i^{(0)}} \\ &\times \left[ \beta_{1,i} (\beta_{1,i} - 1) (1 - SoC_i^{(0)})^{\beta_{1,i}-2} \right. \\ &+ 2\beta_{1,i} \beta_{2,i} (1 - SoC_i^{(0)})^{\beta_{1,i}-1} \\ &+ \left. \beta_{2,i}^2 (1 - SoC_i^{(0)})^{\beta_{1,i}} \right]. \end{aligned} \quad (12)$$

The superscript (0) denotes the value at the operating point. In (11),  $\Delta I C_i$  can be expressed as  $\Delta V_i$  and  $\Delta I_i$  by the chain rule. Because the integrator in (3) exists for the SoC calculation, the supplementary state variable,  $\Delta \dot{V}'_i$ , is introduced to describe the state-space model. This variable is defined as a time derivative of  $\Delta V_i$ . Then, the state-space model of the proposed droop control of a BESS can be expressed as

$$\begin{pmatrix} 0 & 1 \\ 1 & \omega_c \end{pmatrix} \begin{pmatrix} \Delta \dot{V}'_i \\ \Delta V_i \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & m_{IC} \omega_c \frac{I_i^{(0)}}{E_i} \frac{\partial I C_i}{\partial SoC_i} \end{pmatrix} \begin{pmatrix} \Delta V'_i \\ \Delta V_i \end{pmatrix} + \begin{pmatrix} 0 \\ m_{IC} \omega_c \frac{V_i^{(0)}}{E_i} \frac{\partial I C_i}{\partial SoC_i} \end{pmatrix} \Delta I_i. \quad (13)$$

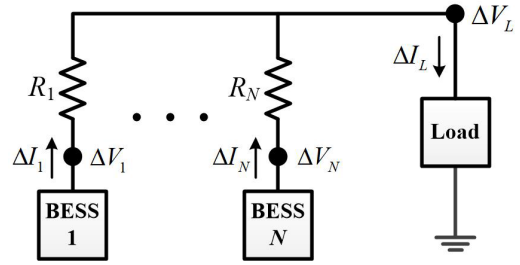


FIGURE 6. Single-line diagram for small-signal stability analysis.

If the total number of BESSs is  $N$ , the state-space model of all BESSs can be expressed as

$$\begin{pmatrix} \mathbf{0} & \mathbf{I} \\ \mathbf{I} & \omega_c \mathbf{I} \end{pmatrix} \begin{pmatrix} \Delta \dot{\mathbf{V}}' \\ \Delta \mathbf{V} \end{pmatrix} = \begin{pmatrix} \mathbf{0} \\ \mathbf{A} \end{pmatrix} \begin{pmatrix} \Delta \mathbf{V}' \\ \Delta \mathbf{V} \end{pmatrix} + \begin{pmatrix} \mathbf{0} \\ \mathbf{B} \end{pmatrix} \Delta \mathbf{I}, \quad (14)$$

where  $\mathbf{I}$  and  $\mathbf{0}$  are an  $N$  by  $N$  identity matrix and an  $N$  by  $N$  zero matrix, respectively,  $\Delta \mathbf{V}' = [\Delta V'_1, \dots, \Delta V'_N]$ ,  $\Delta \mathbf{V} = [\Delta V_1, \dots, \Delta V_N]$ ,  $\Delta \mathbf{I} = [\Delta I_1, \dots, \Delta I_N]$ , and  $\text{diag}(\cdot)$  is a diagonal matrix whose values are the elements of the vector.

Fig. 6 shows the single line diagram of an islanded DC microgrid for small-signal analysis. The load characteristic of the voltage dependency should be included in the state-space model. By Kirchhoff's current law, we have

$$\sum_i \Delta I_i = \Delta I_L(V_L), \quad (15)$$

where  $I_L$  is the load current, which is a function of load voltage,  $V_L$ . The voltage dependency of load can be expressed as a static model or a polynomial model that can be differentiated by voltage [37]. As shown in Fig. 6, since  $V_i = V_L + I_i R_i$  where  $R_i$  is the line resistance between  $i$ th BESS and the load, the relationship of the BESS voltage and current can be derived by replacing  $V_L$  to a function of  $I_i$  using (15), such that

$$\Delta \mathbf{V} = \underbrace{\left\{ \frac{1}{I'_L(V_L^{(0)})} \mathbf{J} + \text{diag}([R_1, \dots, R_N]) \right\}}_{\mathbf{C}} \Delta \mathbf{I}, \quad (16)$$

where  $I'_L$  represents the first-order derivative with respect to load voltage,  $dI_L/dV_L$ , and  $\mathbf{J}$  is a  $N$  by  $N$  matrix whose

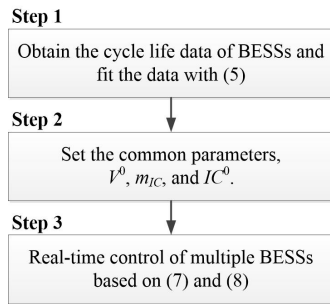


FIGURE 7. Flowchart of the proposed method.

elements are all one. If the load comprises only constant current model,  $V_L$  cannot be expressed as the summation of current deviation of all BESSs using (15), and (16) cannot be used anymore. In this case,  $V_L$  can be eliminated from the relation of  $V_L$  and  $V_i$  (obtained from  $V_i = V_L + I_i R_i$  and  $\sum_i \Delta I_i = 0$ ). However, the composite load model is usually not a constant current because the constant impedance and/or constant current loads such as lightning and data center are common in DC systems [38], [39]. Thus, the details of that case are not described herein. By substituting  $\Delta I$  in (16) into (14), the complete small-signal model is as follows:

$$\begin{pmatrix} \Delta \dot{V}' \\ \Delta \dot{V} \end{pmatrix} = \underbrace{\begin{bmatrix} \mathbf{0} & \mathbf{I} \\ \mathbf{I} & \omega_c \mathbf{I} \end{bmatrix}^{-1} \begin{pmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{A} + \mathbf{B}\mathbf{C}^{-1} \end{pmatrix}}_{\mathbf{D}} \begin{pmatrix} \Delta V' \\ \Delta V \end{pmatrix}. \quad (17)$$

The small-signal stability of an islanded microgrid with the proposed method can be identified by the eigenvalue of state matrix  $\mathbf{D}$  in (17). If all eigenvalues of  $\mathbf{D}$  have a negative real part, the microgrid is small-signal stable.

The flowchart of the proposed method is shown in Fig. 7. The implementation of the IC–V droop control is simple. First, cycle life data of batteries are obtained from the manufacturer, and the curve-fitting parameters in (5) are found. Then, common droop parameters of (8),  $V^0$ ,  $m_{IC}$ , and  $IC^0$ , are set. These can be determined based on the rated voltage, average IC, and stability analysis by the system operator. Each BESS then calculates its IC and makes the output voltage for real-time control using (7) and (8) in a decentralized manner.

## V. CASE STUDIES AND ANALYSIS

To verify the effectiveness of the proposed control method, the test system in Fig. 6 with three BESSs ( $N = 3$ ) was implemented in Matlab/Simulink. The system nominal voltage is 750 V, and the line resistances  $R_1$ – $R_3$  are 0.3  $\Omega$ . The information of the three BESSs are shown in Table 1, and Fig. 8 shows the IC curve of the BESSs between SoC to be 10%–90%. Owing to different cycle life parameters and installation costs, each BESS has a different IC curve. This implies that although the SoC level of the BESSs is balanced, the increment of degradation cost for subsequent operation

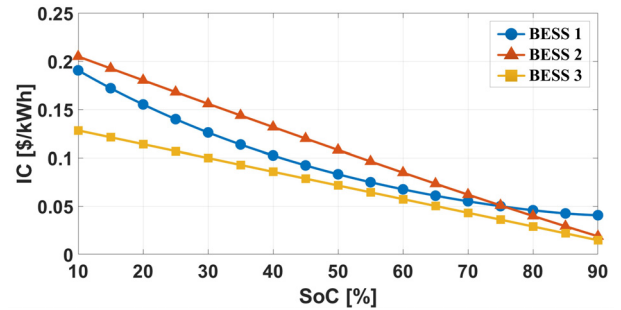


FIGURE 8. IC-SoC curve of three BESSs.

TABLE 1. Information of BESSs.

BESS	$\beta_2$	$\beta_1$	$\beta_0$	$C_{tot}$ [\$]	$E$ [kWh]	$SoC_{ini}$ [%]
1	1.64	0.68	2732	5,500	10	65
2	0	2.089	1591	2,800	8	75
3	1.69	0.19	765	6,300	9	60

may be different. For example, if the SoCs of the BESSs are approximately under 75%, BESS 2 is the most expensive and BESS 3 is cheapest to exchange the same energy. At an SoC above 75%, the IC of BESS 1 is highest, so it is more beneficial for other BESSs to discharge. In other words, from the viewpoint of economic operations, the operating point where all BESSs have the same SoC level may not be the most cost-effective point.

### A. PERFORMANCE OF THE PROPOSED METHOD

The performance of the proposed method is compared with that of the conventional BESS control introduced in Section II.B. To accurately compare the degradation cost between the proposed method and the conventional method, the load consumption should be the same in both methods. If the load demand has voltage dependency, the amount of demand can vary depending on the droop slope and the set-point that affects the grid voltage. This hinders an accurate comparison of the decrease in battery lifetimes by the control methods. Therefore, only a constant power load model was adopted to fix the load demand in this study. The capacity of the BESSs was scaled down to 1/10 of its original value to clearly see the change of the SoC in simulation time. In addition, because we focus on the steady-state performance (not dynamic responses), ideal DC voltage and current sources were used to model the BESSs and the load for simplicity.

The net load was changed in a step-wise manner to clearly demonstrate the performance of the methods, as shown in Fig. 9. The net load can be negative owing to the high RES output. The results of the conventional method and the proposed method are shown in Figs. 10 and 11, respectively. The SoCs of the conventional method were converged to the same value, but those of the proposed method were not balanced in accordance with the IC–V droop control, whose purpose is to converge the ICs to the same value. Thus, unlike the ICs of the

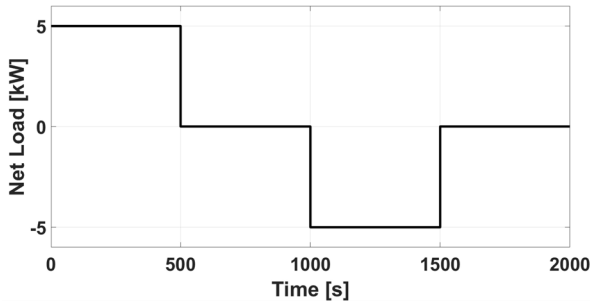


FIGURE 9. Net Load.

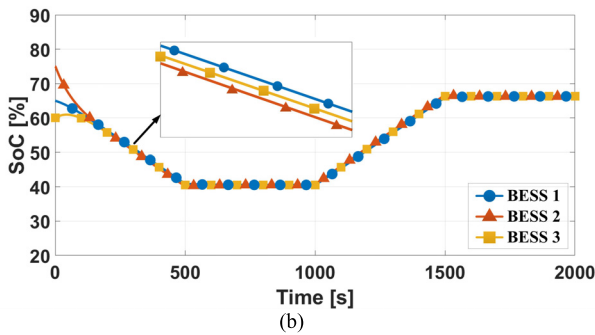
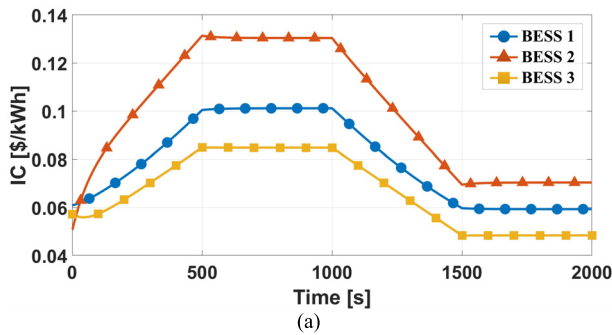


FIGURE 10. Performance of the conventional method: (a) IC and (b) SoC.

TABLE 2. Result of degradation cost.

BESS	Degradation Cost [\$]	
	Conventional method	Proposed method
1	0.3946	0.4009
2	0.4623	0.2572
3	0.2786	0.4354
Total	1.1354	1.0934

proposed method, those of the conventional method had different values. As shown in Figs. 10(b) and 11(a), the SoCs of the conventional method and the ICs of the proposed method were converged to the exact value, when the net load was zero, whereas they were slightly different when the BESSs charged or discharged owing to the line resistance (enlarged part of Figs. 10(b) and 11(a), respectively). However, this effect was not significant as the resistance is quite small in a microgrid.

Table 2 lists the degradation cost of both methods. Although the degradation cost of BESSs 1 and 3 increased,

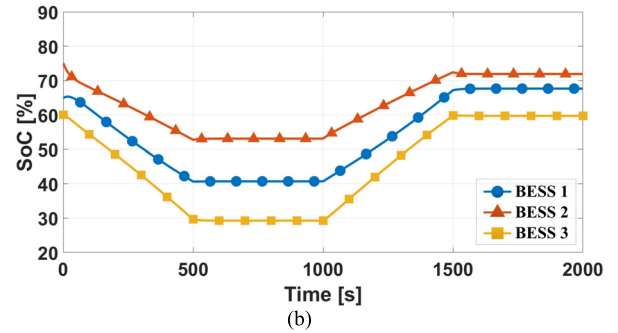
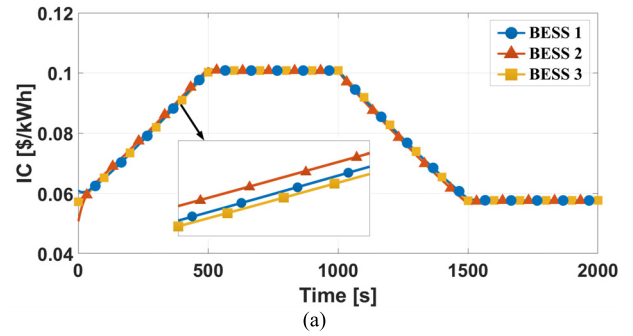


FIGURE 11. Performance of the proposed method: (a) IC and (b) SoC.

the total degradation cost of the proposed method decreased by 3.7% compared to the conventional SoC balancing method. From the IC curve in Fig. 10(a) and Table 2, it can be inferred that in the case of the conventional method, the total degradation cost would decrease if BESS 3 discharged more and BESS 2 discharged less.

### B. SMALL-SIGNAL STABILITY ANALYSIS

To analyze the small-signal stability of the proposed method, the eigenvalue of  $\mathbf{D}$  was plotted at the initial operating point. As the operating point does not converge when only constant power loads exist (continuous voltage drop/rise due to the increase/decrease in ICs of BESS), the same amount of constant resistance load was added to focus on the stability of our proposed method. Fig. 12(a) shows the loci of the three dominant eigenvalues of  $\mathbf{D}$  close to the y-axis for decrease in  $SoC_{ini}$ . (Other eigenvalues are located further left owing to the much larger negative real part.) As the IC is more sensitive to SoC change at low SoC, the operating point converges more rapidly. Likewise, Fig. 12(b) shows the loci of the same three dominant eigenvalues for an increase in  $m_{IC}$  from  $10^4$  to  $10^6$ . A high  $m_{IC}$  improves the small-signal stability by leading to a large deviation in output voltage. The results show that all eigenvalues of  $\mathbf{D}$  had a negative real part; thus, the proposed method is small-signal stable.

### C. DISCUSSION

Similar to the equal IC principle for a conventional economic dispatch problem, the battery degradation cost can be minimized by the same principle with the newly defined IC of BESSs herein. Our proposed method is suitable when the

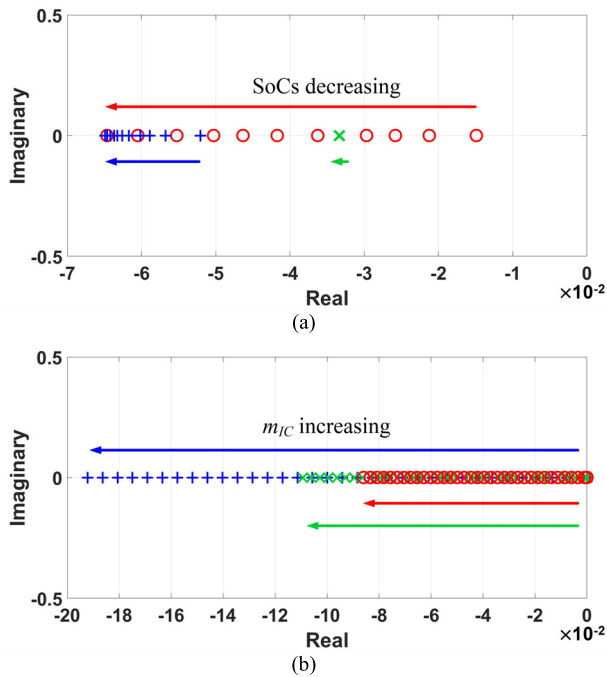


FIGURE 12. Root loci for (a) SoCs decreasing and (b)  $m_{IC}$  increasing.

cost of BESSs does not differ significantly because large difference in cost can cause the BESSs to operate sequentially. Even though the cost difference is small, the proposed method can simultaneously utilize the total installed power capacity of BESSs for less time compared to the SoC balancing method. However, for an islanded operation, the power and energy capacity of BESSs should be conservatively determined to supply energy to loads without collapsing the system. As more BESSs have been installed owing to the high penetration of RES in DC systems, our proposed method can effectively reduce the operation cost while maintaining stability in islanded DC microgrids.

VI. CONCLUSION

A new droop control method of BESSs to reduce the total battery degradation cost for islanded DC microgrid was presented herein. The IC of a BESS was defined from the battery cycle life curve to identify the increment of degradation cost with respect to the current SoC level. Then, to follow the equal IC point in a decentralized manner, the IC-V droop control was adopted in the BESS control, and small-signal stability was analyzed using the state-space model of the proposed method. Case studies show that the proposed method was small-signal stable and reduced the total battery degradation cost compared to the SoC balancing method. Hence, it is anticipated that the proposed control method prolongs the lifespan of BESSs and achieves the economical operation in islanded DC microgrids.

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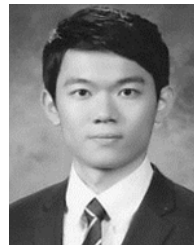
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