Decentralised control strategy for hybrid battery energy storage system with considering dynamical state-of-charge regulation

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Abstract: Hybrid battery energy storage system (HBESS) consists of high power density battery and high energy density battery will have a bright future in special isolated DC microgrid conditions such as the all-electric ships and all-electric airplanes, which have strict limitation on storage capacity and size. In this study, a new decentralised control strategy based on mixed droop is proposed to HBESSs with considering the batteries. In decentralised control strategy, conventional \(V-I\) droop controller is utilised to high energy density battery to mainly supply the steady power, \(I-V\) droop controller is utilised to high power density battery to respond to power change and supply a few steady power. In addition, dynamical state-of-charge (SoC) regulation algorithm is utilised to reassign the battery power according to their own SoC. The power coordination of the high energy density batteries and high discharge rate batteries is achieved by adjusting the values virtual impedance and reference input voltage. Case study shows that the proposed control strategy is flexible and efficient.

Nomenclature

Parameters

- \(L_i, L_2\): converter inductors
- \(R_i, R_2\): summary of battery internal resistance and battery side line resistance
- \(R_{li}, R_{l2}\): line resistance from converter of HPDB and HEDB to the common bus
- \(C_{dc}\): total DC bus capacitor
- \(f_s\): switching frequency
- \(v_{ON}\): DC bus nominal voltage
- \(d_i, d_2\): duty ratio of converters for HPDB and HEDB
- \(g_{V1}\): virtual admittance of \(V-I\) droop control
- \(R_{V2}\): virtual resistance of \(V-I\) droop control
- \(k_{iP}, k_{iP}\): current loop parameters for HPDB and HEDB
- \(k_{iV}, k_{iV}\): voltage loop parameters for HEDB
- \(k_{iV}, k_{iV}\): voltage compensator controller parameters for HPDB and HEDB
- \(w_c\): cutting frequency
- \(V_{omin}\): available minimum bus voltage
- \(P_{HESS}\): power of HESS
- \(P_{PCL}, P_{CPS}\): power of PCL, CPS
- \(V_{bus}\): bus voltage at load terminal point
- \(V_{dcl1}, V_{dcl2}\): bus voltage at the \(i\)th HPDB and HEDB
- \(i_{HESS}\): total current of all energy storage units
- \(i_{sdcl1}, i_{sdcl2}\): current of the \(i\)th HPDB and HEDB
- \(i_{ref}\): actual reference voltage for the primary control
- \(v_{ON}\): nominal voltage when load power is zero
- \(v_{min}, v_{max}\): port voltage of HPDB and HEDB
- \(I_{min}, I_{max}\): output current of HPDB and HEDB at the converter input side
- \(I_{omax}, I_{omin}\): maximum permit output current of HPDB and HEDB at the converter output side
- \(dV_{c}, dV_{soc}\): result of voltage restoration control and SoC regulation control
- \(Q_{0}\): rated capacities of the battery
- \(SOC_{min}\): battery initial SoC level
- \(SOC_{crit}\): maximum SoC which permit to charge
- \(SOC_{min}\): minimum SoC which permit to discharge
- \(SOC_{hj}\): maximum SoC which does not limit charge
- \(SOC_{low}\): maximum SoC which does not limit discharge

1 Introduction

With the gradual increase of energy demand and global emissions of greenhouse gases, many new challenges have emerged in the existing power system [1]. As one of the promising technologies, microgrids [2] have attracted more attentions in recent years. According to a relatively small-scale localised energy network [3–5], microgrid can effectively integrate high penetration level of distributed energy resources, such as energy storage systems and distributed generators. In all microgrid technologies, shipboard microgrid [6–9] also called as integrated power system is gaining increasing attention since the marine transport produce huge amounts of greenhouse gases and shipboard microgrid technology can effectively improve the onboard energy systems efficiency. In order to achieve minimal greenhouse gases emission, renewable energy resources is also introduced into the microgrid.

However, uncertainties associated with the renewable energy and load profile raise critical challenges in designing a stable system, so energy storage system play a crucial role in shipboard microgrid [10, 11]. Different from the land microgrid, the impact of load uncertainty is larger than the renewable energy, since ship power is mainly consumed by propulsion load and its profile can significantly vary in relation to weather conditions and operational requirements.

An ideal energy storage system should have high energy density, high power density, long cycle life and low cost [12], it not only can fast response to the transient power change but also can achieve continuous power supply. However, no existing energy storage technologies satisfy the above requirement. Supercapacitor (SC) [13] has high power density and long cycle life, but its energy density is very low; wide used lithium ion battery [14] in vehicle cars has high energy density but its power density is low and its discharge rate is very small; the feature of flywheel [15] is similar to SC. Recently, high power density battery (HPDB) which with high discharge rate [16, 17] and high energy density capacitors [18]...
have been produced and applied to some special conditions such as rail transport and electrical ship. Comparing to the conventional high energy density batteries (HEDBs), the discharge rate of HPDBs increases a lot, they can continuously discharge power excess 15 C. In microgrids which have strict limitation on storage capacity and size, such as the all-electric ships and all-electric airplanes, HPDBs can replace SCs and flywheels because HPDBs have both advantages in high energy density and high power density. The main shortcomings of HPDBs are that their short cycle life comparing with SCs and high investment cost comparing with HEDBs. The contradiction between the long cycle using life and small deployment space cannot be perfectly solved with current technology, however, can be partly solved by restricting the depth-of-discharge of HPDBs and optimise the HPDBs discharge process. The solution of reducing high investment of HPDBs is to integrate a few HEDBs to increase the energy density of the energy storage system [19, 20]. This hybrid energy storage system of HEDBs and HEDBs is called as hybrid battery energy storage system (HBESS). In order to extend the cycle using life of HBESS, suitable topology and coordination control mechanism should be proposed to be utilised in this special application condition.

Various HBESS topologies based on their connection topology have been proposed to optimise the system dynamic performance [21]. Based on lots of tests, the active connection topology was proved the most flexible topology; it not only can effectively coordinate the energy storages with different ramp rates but also has high system reliability. Therefore, active connection topology is applied to HBESS.

Similarly, there are many control strategies that are proposed to coordinate the power output of different energy storage components. From the communication's perspective, there are centralised and decentralised control strategies. In [24, 25], filter-based control strategies are utilised in a central controller to generate high/low frequency power references for SCs and HEDBs. In [26], model predictive control is utilised in a central controller to generate high/low frequency power references for SCs and HEDBs. Though there are many advantages for centralised control strategy, the communication delays and single point-of-failure issues are its shortcoming, and this shortcoming may cause detrimental effect on the operation performance. In [27], a decentralised control strategy is proposed. All energy storage units are equally controlled according to their local bus signal, no information exchange among converters is required, and hence it is conceived to be the most reliable one among all control methods. Droop control is the most widely used decentralised control method.

Further, droop control can also be divided into several algorithms according to different control theory, they are conventional voltage- droop and current- droop controller, voltage-current (V–I) droop algorithm and integrate droop (ID) algorithm. ID algorithm was inspired by investigating the characteristics of capacitors, hence it is mainly applied to SCs or flywheels. V–I droop algorithm and V–I droop algorithm can be used for all types of energy storages. Literature [28] proved that V–I droop control algorithm has faster dynamic response capability than conventional V–I droop control algorithm, however, the damping performance of V–I droop control algorithm is a little inferior to the V–I droop control algorithm. In addition, Literature [29] proves that V–I droop control algorithm and V–I droop control algorithm can be fully compatible with each other.

In order to achieve current sharing among different types of energy storage units in a decentralised way, a few modified decentralised control strategies are proposed. In [30], filter-based V–I droop control algorithm was proposed, the high-pass filter (HPF) and a low-pass filter (LPF) were used to decompose the load power demand into high/low frequency components. In [24, 31], filter-based V–I droop control algorithms were proposed to assign the power between the SCs/flywheels and HEDBs. In [32], a mixed droop control method which consists of ID and V–I droop was proposed to assign the power between the SCs and HEDBs. However, no coordination control strategies for HBESS are discussed before, and few literatures focus on the mixed droop control strategy of V–I droop and V–I droop.

Additionally, a few literatures are focused on lengthening cycle life and ensuring safety operation of batteries. In [33], a reference value based state-of-charge (SoC) recovery rule was proposed, the discharge/charge power is determined by the difference between the preset reference SoC and the actual SoC. Simulation shows that though this SoC recovery rule can effectively preserve the safety operation of energy storage units, the flexibility is strictly limited. In [29], a SoC based storage regulation algorithm was proposed, the storage droop coefficient is dynamically adjusted according to the magnitude of SoC. However, the relationship model between SoC and droop coefficient is very complex, a simple and flexible SoC regulation algorithm should be proposed.

In this paper, we focused on proposing a new mixed droop based decentralised control strategy (nMDCS) of HBESS to reliably and flexibly coordinate the different kinds of batteries. This nMDCS has three control levels, the primary control level, bus voltage restoration level and SoC regulation level. At the primary control level, a mixed droop control strategy of V–I droop and V–I droop is proposed to share the current between the HEDBs and the HPDBs according to their difference discharge rate feature. Conventional V–I droop controller is utilised to HEDBs to mainly supply the steady power since their discharge rate is low, meanwhile, V–I droop controller is utilised to HPDBs to respond to transient power change and supply a few steady power with HEDBs since their discharge rate is high and they can store much more energy than SCs/flywheels. In the bus voltage restoration level, a conventional proportional and integral (PI) based voltage restoration model is implemented to make the bus voltage can be always stabilised at the preset value. In the SoC regulation level, a decentralised multi-level SoC regulation algorithm is proposed, different regulation models in different SoC levels are utilised to balance the SoC of different batteries.

The rest of the paper is organised as follows. Section 2 describes the DC microgrid and the proposed HBESS control strategy. Section 3 presents performance comparison with small-signal modelling methods. The simulation setup is described in Section 4 and Section 5 shows the simulation results and discussions. Section 6 concludes this paper.

2 System description and control strategy modelling

A typical scheme of a shipboard DC microgrid including HBESS, wind turbines, photovoltaic (PV) panels and kinds of loads are shown in Fig. 1a. Wind and PV generators are operated in maximum power point tracking mode, and thus can be considered as constant power sources (CPSs) [34]. On the contrary, most loads connected by power electronic converters are considered as constant power loads (CPLs). HBESS is acted as the main source, and it consists of HEDBs and HPDBs and connected to the DC bus with active topology. The control framework of HBESS is shown in Fig. 1b.

HBESS power is equal to the difference of CPSs and CPLs

\[ P_{\text{HBESS}} = P_{\text{CPS}} - P_{\text{CPL}} \]  

where \( P_{\text{CPS}}, P_{\text{CPL}} \) and \( P_{\text{HBESS}} \) represent the CPSs power, CPLs power and HBESS power, respectively.

On the other hand, HBESS power can be illustrated as [31]

\[ P_{\text{HBESS}} = \frac{P_{\text{HBESS}}}{V_u} \]  

where \( P_{\text{HBESS}} \) and \( V_u \) denote HBESS output current and bus voltage, respectively.

As is known to all, resistance loads increase system damping coefficient [35], but CPLs/CPSs decreases system damping coefficient. Therefore, if the proposed HBESS control strategy can handle the microgrid of Fig. 1a stable and efficient, it also can work well in other conditions.

As shown in Fig. 1b, a hierarchical control framework is utilised to the HBESS. The outputs of bus voltage restoration...
control and SoC regulation control are acted on the primary control level to adjust the input voltage reference of it.

3 Description of nMDCS

3.1 Mixed droop based primary control

The primary control is designed to stabilise the bus voltage and to offer plug and play capability for loads and resources. It provides the input reference value for inner voltage and current control loops. 

$V-I$ droop is achieved by linearly adjusting the voltage reference around the nominal voltage when the output current changes. It is presented as

$$u_{ref} = u_{dc} - R_v \cdot I_{dc}$$

where $u_{dc}$, $u_{dcN}$ and $I_{dc}$ denote the DC bus reference voltage, nominal output voltage and the converter output current, respectively. $R_v$ is the virtual resistance.

The magnitude of $R_v$ is solved by

$$R_v = \frac{u_{dcN} - u_{min}}{I_{omax}}$$

where $u_{min}$ is the minimum permit bus voltage, $I_{omax}$ is the maximum permit output current.

If there are multiple converters and they are all controlled by $V-I$ droop control algorithm, the power sharing relationship among these converters can be presented as

$$R_{V1} \cdot I_{d1} = \cdots = R_{Vn} \cdot I_{dn} = \cdots = R_{V2k} \cdot I_{d2k}$$

(5)

where $R_{Vi}$ and $R_{Vn}$ ($i = 1, 2, \ldots, n$) denote the output current and virtual resistance of the $i$th converter, respectively.

$I-V$ droop designs an embedded virtual impedance to replace the voltage loop to improve the response capability. In order to be compatible with the conventional $V-I$ droop control, its mathematical formulation is presented as

$$I_{d1} = (u_{dcN} - u_{dc})g_{v1}$$

(6)

where $I_{d1}$ and $V_{d1}$ represent output reference current and output voltage of converter, respectively. $g_{v1}$ is the $I-V$ droop coefficient. If the rated power of connected converters are the same, the relationship between $I-V$ droop coefficient and $V-I$ droop coefficient can be expressed as

$$g_{v1} = 1/R_v$$

(7)

Similarly, if there are multiple converters controlled by $I-V$ droop, the power sharing among them can be obtained as

$$I_{d1} \cdot V_{d1} = \cdots = I_{d2k} \cdot V_{d2k} = \cdots = I_{dcm} \cdot V_{dcm}$$

(8)

where $I_{dik}$ and $V_{dik}$ ($k = 1, 2, \ldots, n$) are the output current and droop coefficient of the $k$th converter, respectively.

If we neglect the line resistance, the voltage signals of $V-I$ droop and $I-V$ droop control are the same. That is

$$V_{dik} = V_{d2k} = V_{bus}$$

(9)

where $V_{bus}$ represents the common bus voltage, $V_{d2k}$ represents the obtained voltage signal for $I-V$ droop controller and $V_{d2k}$ represents the obtained voltage signal for $V-I$ droop controller.

The current sharing between HEDBs controlled by $V-I$ droop algorithm and HPDBs controlled by $I-V$ droop algorithm can be presented as

$$\frac{I_{dik}}{I_{d2k}} = \frac{1/R_{V2k}}{g_{v1}}$$

(10)

3.2 PI-based bus voltage restoration control

The bus voltage with droop control will be diverged from the nominal value once the system power varies from the set value. Therefore, a bus voltage restoration control should be implemented to restore the bus voltage back to the nominal value.

In this paper, a PI-based bus voltage restoration control is utilised as follows:

$$dV_i = k_{dvp}(u_{dcN} - v_{bus}) + k_{dvi}\int (u_{dcN} - v_{bus})$$

(11)

where $dV_i$ is the voltage compensator, $k_{dvp}$, $k_{dvi}$ represent PI parameters, respectively.

The bus voltage restoration control is used to adjust the voltage reference of primary control, as shown in Fig. 2a. If HBESS discharges with current $I_{dis}$, the bus voltage will drop $dV_q$ because of droop control characteristics, in order to make the bus voltage back to nominal value, a voltage compensator must be implemented. If HBESS charges, the action of bus voltage restoration control is the similar.

3.3 Piecewise linearisation optimisation based SoC regulation control

To better regulate the charge or discharge process of HBESS, and extend the cycle life of HPDBs and HEDBs, a piecewise linearisation optimisation based SoC regulation algorithm is proposed. Therefore, the actual power output of a battery is not only determined by the droop coefficient but also affected by its
own SoC value. Different SoC values have different regulation outputs. Its scheme is shown in Fig. 2b.

In Fig. 2b, the battery SoC is divided into five intervals. When \( \text{SoC}_{\text{low}} \leq \text{SoC} \leq \text{SoC}_{\text{high}} \), it is in the green operation area, the battery output is only determined by droop coefficient, SoC regulation algorithm has no affection on it. When \( \text{SoC}_{\text{min}} \leq \text{SoC} \leq \text{SoC}_{\text{low}} \), the battery is in the limited discharge area, its discharge power will be ruled by the SoC regulation algorithm. On the contrary, when \( \text{SoC}_{\text{high}} \leq \text{SoC} \leq \text{SoC}_{\text{max}} \), the battery is in the limited charge area, its charge power will be ruled by the SoC regulation algorithm. In addition, when \( \text{SoC} \leq \text{SoC}_{\text{min}} \), the battery prohibits discharging and when \( \text{SoC} \geq \text{SoC}_{\text{max}} \), the battery prohibits charging.

The detailed mathematical model of SoC regulation algorithm is expressed as follows: (see (12)) where \( \text{SoC} \), \( h_{\text{bus}} \) and \( G_{\text{SoC}} \) represent the battery SoC value, battery output current and the regulation algorithm output, respectively.

As we all know, the time granularity of primary control and SoC regulation control are different. The time granularity of primary control is much larger than the time granularity of SoC regulation control, namely, there is a time delay between the primary control and the SoC regulation control. Due to the time delay is small, a LPF is introduced [29] to act as the time delay between the primary control and SoC regulation control

\[
G_{\text{SoC}} = \frac{dV_{\text{soc}}}{1 + Ts}
\]  

(13)

Considering the impacts of SoC regulation control and voltage restoration control, the final bus voltage reference for \( V-I \) droop and \( I-V \) droop controllers are calculated as

\[
u_{\text{ref}} = u_{\text{n}} + dV_{i} + dV_{\text{soc}}
\]  

(14)

Then, the input signal for the inner loop of \( V-I \) droop controller is expressed as

\[
u_{12}^* = u_{\text{ref}} - R_{\text{dc}}i_{\text{dc}}
\]  

(15)

Meanwhile, the input signal for the inner loop of \( I-V \) droop controller is shown as

\[i_{\text{dc}}^* = (u_{\text{ref}} - v_{\text{dc}})g_{v}
\]  

(16)

### 4 Stability analysis by small-signal modelling

In order to analyse the dynamic and stability characteristics of the proposed control strategy in this paper, the state-space equations of the microgrid in Fig. 1a are established, then the small-signal model is utilised to analyse the performance.

#### 4.1 Main circuit model

\[
L_{1} \frac{di_{L1}}{dt} = d_{1}(V_{\text{in}} - R_{e}i_{L1}) - v_{\text{dc}} - R_{0}i_{L1}
\]

\[
L_{2} \frac{di_{L2}}{dt} = d_{2}(V_{\text{in}} - R_{e}i_{L2}) - v_{\text{dc}} - R_{0}i_{L2}
\]

\[
C_{\text{dc}} \frac{dv_{\text{dc}}}{dt} = i_{L1} + i_{L2} - i_{\text{CPLS}}
\]

\[
i_{L1} = d_{L1}i_{L1} - i_{0n} = d_{L1}i_{L1}
\]

As shown in Fig. 1b, \( V_{\text{in}}, i_{L1} \) and \( R_{e} \) represent input voltage, current and equivalent resistance for HPDB’s converter, \( R_{0} \) and \( i_{L2} \) represent output resistance and current for HPDB’s converter, \( d_{1} \) represents the duty ratio of HPDB’s converter. \( V_{\text{bus}}, i_{L1} \) and \( R_{e} \) represent input voltage, current and equivalent resistance for HEDB’s converter, \( R_{0} \) and \( i_{L2} \) represent output resistance and current for HEDB’s converter, \( d_{1} \) represents the duty ratio of HEDB’s converter. \( C_{\text{dc}} \) represents the aggregated capacitor in the microgrid.

Small-signal model of the main circuit is derived by linearising it around the operating point as

\[
\Delta \dot{x} = A_{1}\Delta x + B_{1}\Delta u
\]

where \( \Delta x = [\Delta i_{L1}, \Delta i_{L2}, \Delta v_{\text{bus}}]^T \), \( \Delta u = [\Delta d_{1}, \Delta d_{2}]^T \)

\[
A_{1} = \begin{bmatrix}
\frac{-R_{e}D_{1}^{2} - R_{0}}{L_{1}} & 0 & -1/L_{1} \\
0 & \frac{-R_{e}D_{2}^{2} - R_{0}}{L_{2}} & -1/L_{2} \\
\frac{1}{C_{\text{dc}}} & \frac{1}{C_{\text{dc}}} & \frac{P_{\text{CPLS}}}{C_{\text{dc}}V_{\text{bus}}}
\end{bmatrix}
\]

\[
B_{1} = \begin{bmatrix}
\frac{V_{\text{in}} - 2R_{e}D_{1}I_{L1}}{L_{1}} & 0 \\
0 & \frac{V_{\text{in}} - 2R_{e}D_{2}I_{L2}}{L_{2}} \\
0 & 0
\end{bmatrix}
\]

where \( D_{1} \) and \( I_{L1} \) represent the duty ratio and converter output current at steady state for HPDB, \( D_{2} \) and \( I_{L2} \) represent the duty ratio and converter output current at steady state for HEDB, \( V_{\text{bus}} \) is the steady-state voltage for microgrid common bus.
4.2 Mixed droop based primary control

Primary control is modelled based on Fig. 1b. The control loop of HPDB is derived as

$$X_{i1} = (u_{dN} - v_{bus} + dV_Y + dV_{soc}) i_{11} \quad (19)$$

$$X_{i1} = i_{e1} - i_{11} \quad (20)$$

$$d_i = k_{i0}x_{1i} + k_{ip}x_{11} \quad (21)$$

where $X_{i1}$ represents the output of current loop; $i_{e1}$ represents the reference current; $k_{i0}$ and $k_{ip}$ represent current loop PI parameters.

Similar to the model of HPDB, the primary control model of HEDB is expressed as

$$X_{i2} = u_{dN} + dV_Y + dV_{soc} - R_{i2}i_{12} - v_{bus} \quad (22)$$

$$i_{e2} = k_{i0}x_{21} + k_{ip}x_{22} \quad (23)$$

$$X_{i2} = i_{e2} - i_{12} \quad (24)$$

$$d_i = k_{i0}x_{2i} + k_{ip}x_{22} \quad (25)$$

where $X_{i2}$ and $X_{i1}$ represent the outputs of voltage loop and current loop, respectively; $i_{e2}$ represents the reference current; $k_{i0}$ and $k_{ip}$ represent the voltage loop PI parameters and $k_{i0}$ and $k_{ip}$ represent the current loop PI parameters.

Combining (20) and (24) and performing a small-signal disturbance, the control inputs of primary control based on small-signal analysis are expressed as

$$\Delta u_i = B_{i1}\Delta x_1 + B_{i2}\Delta x_2 + B_{i3}\Delta x_3 + B_{i4}\Delta x_4 \quad (26)$$

where

$$\Delta u_i = [\Delta i_1, \Delta i_2]^T, \quad \Delta x_1 = [\Delta X_{i1}, \Delta X_{i2}, \Delta X_{i3}, \Delta X_{i4}]^T, \quad \Delta x_2 = \Delta dV_Y, \quad \Delta x_3 = [\Delta dV_{soc}, \Delta dV_{soc}]^T$$

represent control vector for main circuit, state vector for controller variables, input vector from the secondary control level and input vector from the tertiary control level, respectively.

The coefficient vectors are calculated as (see equation below). Meanwhile, $\Delta x_2$ can be expressed as

$$\Delta x_2 = A_{i1}\Delta x_1 + A_{i2}\Delta x_2 + A_{i3}\Delta x_3 + A_{i4}\Delta x_4 \quad (27)$$

where

$$A_{i1} = \begin{bmatrix} -1 & 0 & -g_{i1} \\ 0 & -R_{i1}k_{ip} - 1 & -k_{ip} \\ 0 & -R_{i2} & -1 \end{bmatrix}, \quad A_{i2} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 1 & 0 & 1 \end{bmatrix}$$

If there is a communication failure, the input vector from the secondary and tertiary controller is zero and make the system operate only with primary control. The small-signal model of HBEES only utilised by primary controller can be obtained as

$$\frac{\Delta x_2}{\Delta x_1} = \begin{bmatrix} A_{i1} + B_{i1}B_{i1} & B_{i1}B_{i2} \\ A_{i2} & A_{i2} \end{bmatrix} \frac{\Delta x_1}{\Delta x_1}$$

(28)

4.3 Bus voltage restoration control

Voltage restoration control is expressed as

$$X_{dv} = u_{dN} - v_{bus} \quad (29)$$

$$dV_Y = k_{dvp}X_{dv} + k_{dvs}X_{dv} \quad (30)$$

where $X_{dv}$ represents the state variable of the secondary control level, $dV_Y$ represents the output of the secondary control level, and $dV_Y$ is output of voltage restoration level controller, respectively; $k_{dvp}$ and $k_{dvs}$ are controller PI parameters.

Performing a small-signal disturbance on (30), the control input of the secondary control based on small-signal analysis is expressed as

$$\Delta x_1 = A_{i1}\Delta x_1 + A_{i2}\Delta x_2 + A_{i3}\Delta x_3 + A_{i4}\Delta x_4 \quad (31)$$

where

$$\Delta x_2 = \Delta X_{dv}, A_{i1} = [0 \quad 0 \quad -k_{dvp}], A_{i2} = k_{dvs}.$$ $\Delta x_2$ can be expressed as

$$\Delta x_2 = A_{i1}\Delta x_1$$

(32)

4.4 Dynamical SoC regulation control

Based on the definition, SoC of a battery can be obtained as

$$SOC_x = SOC_{init} - \frac{\int_{init}^x df}{Q_x} \quad (33)$$

where $x$ represents the battery index, $Q_x$ and $P_{max}$ are the capacity and power of ES $x$. According to (33), the affection of variations of bus voltage and current cannot appear immediately in the dynamical SoC regulation control. Hence, in the small-signal modelling of dynamical SoC regulation control, the variations of bus voltage and current are both neglected.

Moreover, in order to reduce the communication burden and satisfy the superior control requirement, a first-order LPF for the SoC-based voltage compensator order

$$dV_{soc} = G_{soc} \frac{w_c}{s + w_c} \quad (34)$$

where $w_c$ is the cutting frequency of the LPF. Performing small-signal disturbance to (32), the small-signal model of the dynamical SoC regulation control is expressed as

$$\Delta x_1 = A_{i1}\Delta x_1$$

(35)

The above small-signal model indicates that the SoC regulation control operation has little impaction on operation stability.

Therefore, the small-signal model of the HBEES with the proposed nMDCS is obtained as

$$B_{i1} = \begin{bmatrix} -k_{ip} & 0 & -g_{i1}k_{ip} \\ 0 & -R_{i1}k_{ip} - k_{ip} & -k_{ip}k_{ip} \\ k_{ip} & 0 & k_{ip}k_{ip} \end{bmatrix}, \quad B_{i2} = \begin{bmatrix} g_{i1}k_{ip} \\ k_{ip}k_{ip} \end{bmatrix}, \quad B_{i3} = \begin{bmatrix} g_{i1} \end{bmatrix}, \quad B_{i4} = \begin{bmatrix} 0 \end{bmatrix}$$
5 Simulation and results analysis

In this section, the performance of V–I droop control algorithm and I–V droop control algorithm will be firstly compared. Then, the stability analysis of the proposed nMDCS will be conducted. Impacts of CPL and system parameters are investigated. Finally, the performance comparison between the proposed nMDCS and other decentralised control strategies are compared.

The simulation is conducted in PSCAD 4.5.2 and Matlab 2013a. Controller parameters are listed in Table 1.

5.1 Dynamics comparison for V–I droop and I–V droop

By setting the average inductor current as the output, the root locus method has been utilised to analyse the dynamic characteristics of V–I and I–V droop controls. The controller parameters of the two droop controls are listed in Table 1.

Setting the difference of CPL and CPS as 2 kW and setting other parameters as Table 1, the poles of the I–V droop and V–I droop controls are listed in Fig. 3a. It indicates that I–V droop control is a little more stable than V–I droop control due to the maximum pole value of the I–V droop control is closer to the right half plane than I–V droop control. Setting controller parameters as in Table 1 and by changing the difference of CPL and CPS from 0.1 to 10 kW, the pole shifting trajectories of the two droop control algorithms are shown in Fig. 3b. It indicates that as the power of the CPL demand increasing, the stability of the two droop controls deteriorate rapidly. The unstable power for V–I and I–V droop controls are 2.8 and 2.5 kW, respectively. This result verifies that the damping characteristics of V–I droop control are a little better than I–V droop control.

5.2 HBESS stability analysis

Setting the difference of CPL and CPS as 2 kW and by changing the droop coefficient of I–V droop from 0.1 to 40 and V–I droop from 10 to 0.025, the pole shifting trajectories of the two droop control algorithms are shown in Fig. 3c. Firstly, it indicates that if the changed coefficients all from one droop control model, HBESS can still be stable, however, if both the two droop control coefficients are changed, HBESS probably become unstable. Secondly, it indicates that if the droop coefficient of droop control is large, the dynamic response performance of the HBESS will degrade and the capability of keeping stability will fall severely. Thirdly, a large DC bus capacitor can effectively improve the stable performance of HBESS.

Additionally, in order to evaluate the performance of the proposed control strategy, a 30 s perturbed CPLS power, which is equal to net power of CPL minus CPS, simulation is conducted in PSCAD. The system net power is from −2.8 to 2.8 kW, as shown in Fig. 3e. The parameters of ES devices are listed in Table 2 and the simulation results are shown in Figs. 3d and e.

Fig. 3e indicates the effectiveness of the primary control and secondary control method utilised in this paper. The mixed droop primary control can effectively retrain the change of bus voltage within a certain range, and the bus voltage restoration algorithm can timely restore the stable voltage back to the nominal value. Since CPLs are known to have negative impedance characteristics, which may destabilise the DC bus, however, CPSs have positive impedance characteristics, which can stabilise the DC bus. Therefore, the bus voltage shocks severely when CPL power near

\[
\begin{bmatrix}
\Delta x_1 \\
\Delta x_2 \\
\Delta x_3 \\
\Delta x_4 \\
\Delta x_5 \\
\Delta x_6
\end{bmatrix} = \begin{bmatrix}
A_{11} & B_{12} & B_{13} & B_{14} & B_{15} & 0 \\
A_{21} & A_{22} & A_{23} & 0 & 0 & 0 \\
A_{31} & 0 & 0 & A_{33} & 0 & 0 \\
0 & 0 & 0 & A_{44} & 0 & 0 \\
A_{51} & 0 & 0 & 0 & A_{55} & 0 \\
0 & 0 & 0 & 0 & A_{66} & 0
\end{bmatrix} \begin{bmatrix}
\Delta x_1 \\
\Delta x_2 \\
\Delta x_3 \\
\Delta x_4 \\
\Delta x_5 \\
\Delta x_6
\end{bmatrix} (36)
\]

It should be mentioned that this modelling process can also be applied to different kinds of HESS such as SC-battery system, flywheel-battery system and so on.

![Fig. 3 Stability analysis for the proposed control strategy](image)

(a) Eigenvalue loci of two droop control algorithms, (b) Impacts of varying CPL power on the eigenvalue loci, (c) Impacts of varying droop coefficients on the eigenvalue loci, (d) Net power of CPLS, (e) Bus voltage with perturbed CPLS power, (f) battery SoC of with complete nMDCS, (g)SoC without SoC regulation, (h)Current of with complete nMDCS, (i) Current without SoC regulation

Table 1 System parameters

| Variables | Value | Variables | Value |
|-----------|-------|-----------|-------|
| $L_{c1}, L_{c2}$ | 1.8 mH, 1.8 mH | $v_{r1}$ | 20 s |
| $R_{c1}, R_{c2}$ | 0.01 Ω, 0.01 Ω | $R_{n1}$ | 0.05 Ω |
| $R_{ci}, R_{oi}$ | 0.001 Ω, 0.001 Ω | $k_{ii}, k_{ip}$ | 0.01, 0.001 |
| $C_{di}$ | 2200 μF | $k_{r1}, k_{r2}$ | 1, 10 |
| $f_s$ | 2 kHz | $k_{di}, k_{dp}$ | 2, 3 |
| $u_{dm}$ | 100 V | $w_c$ | 2 |
| $V_{in1}, V_{in2}$ | 230 V, 230 V | $V_{min}$ | 90 V |
Comparing Fig. 3 limited discharge power area and reduce the charge power when its SoC is in the limited charge power area. Figs. 3h and i present the currents of HPDBs and HEDBs, respectively. Due to the SoC violation is not very significant in this case, the currents of the two figures are nearly the same, and however, once the SoC goes into the limited operation area, such as in 3–5 s, differences also can be found.

5.3 Comparing with other HBESt control strategies

In this subsection, four other commonly used decentralised control strategies are introduced to control the HBESt to evaluate the performance of the proposed nMDCS.

(i) Mixed droop control strategy consisting of ID and V–I droop (shorted as VCRS): It is proposed in [36] and obtained many attentions in near years. ID is applied to HPDBs and V–I droop control is applied to the HEDBs.

(ii) Double V–I droop control strategy (shorted as DVIS). It is the most common used control strategy, V–I droop control is applied to all the connected batteries.

(iii) Filter-based V–I droop control strategy (shorted as FVIS) [24]. It is also a common used control strategy, HPF based V–I droop control is applied to HPDBs and LPF based V–I droop control is applied to HEDBs.

(iv) Filter-based I–V droop control strategy (shorted as FIVS). It is proposed in [30] and the theory is similar to FVIS. HPF-based I–V droop control is applied to HPDBs and LPF-based I–V droop control is applied to HEDBs.

In order to comprehensively evaluate the performance of the above four control strategies and the proposed nMDCS, a variable resistive load is integrated into the previous case study, namely there are CPLs, CPSs and resistive loads in the microgrid. The power demand of this resistive load is shown in Fig. 4a, it is varied from 0.5 to 20 kW. Additionally, in order to more clearly compare the performance, SoC regulation control is not considered to the above four strategies.

In Figs. 4b–f, nMDCS acts the best in stabilising the bus voltage over the whole simulation horizon, its bus voltage deviation is always controlled within 4%, the following is FIVS. However, due to the damping characteristics of FVIS, the transient response to load change is a little inferior to nMDCS.

Meanwhile, though the SoC regulation control is considered for all the five control strategies, there also significant difference to SoC variation routines for all the five control strategies. Since VCRS, FVIS and FIVS are just proposed for HESS of SC/battery or flywheel/battery, where the energy density of power type energy storage component is very low. Once apply these control strategies to HBESt, the stored large-scale energy of HPDBs cannot be discharged, and the advantage of HPDBs cannot be played.

Moreover, if parts of the ESS components are failed, only nMDCS and DVIS can well stabilise the bus voltage. The other control strategies are all based on different kinds of filters, the power output of each battery is assigned before and may not be replaced.

In addition, the performance of SoC regulation control algorithm is displayed in Fig. 4g. The rate capacity of HPDB and HEDB are both increased to 1 Ah, the minimum SoC values are reduced to 0.45 and 0.5, respectively. Due to the available energy of HEDB is less than HPDB, HPDB discharge more power than HEDB. Combining with Fig. 3f, it can be concluded that SoC regulation control algorithm can effectively adjust the power of all storage units in the HBESt.

6 Conclusion

With the development of technology, HPDB and high energy density capacitors will be more and more attracting for some special situations, such as ship, airline and so on. The hybrid of HPDBs and usually HEDBs will become true in the near future. This paper proposes a new decentralised control strategy with three levels, the primary control level, bus voltage restoration level and SoC regulation level. The state-space equations based on small-
signal model is established to analyse the dynamic performance and stability of the proposed control strategy. Case study shows that the proposed nMDCS can effectively stable system bus voltage and regulate SoC variations of different kinds of batteries.

Future work will focus on improving the SoC regulation methods and discussing the implications introduced by line impedance.

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