Cooperative Control of Distributed Heterogeneous Energy Storage Devices with Virtual Impedance

Runfan Zhang, Branislav Hredzak
School of Electrical Engineering and Telecommunications
University of New South Wales
Sydney, NSW 2052 Australia
runfan.zhang@student.unsw.edu.au,
b.hredzak@unsw.edu.au

Thomas Morstyn
Department of Engineering Science
University of Oxford
Oxford OX1 3PJ, United Kingdom
thomas.morstyn@eng.ox.ac.uk

Abstract—This paper proposes a cooperative control for power sharing and energy balancing between heterogeneous energy storage devices, improving reliability, flexibility, and scalability. The batteries are controlled in a distributed fashion, over a sparse communication network, while decentralized control is used for the ultracapacitors. The virtual impedance control strategy allocates the high frequency component of the loads to the ultracapacitors and the low frequency component to the batteries, without using filters. Presented simulation results verify the performance of the proposed strategy for an islanded DC microgrid with variable loads.

Keywords—cooperative control; virtual impedance control; heterogeneous storage devices; DC microgrid

I. INTRODUCTION

Renewable energy sources with no dispatchability and intermittent operation, such as wind turbines and photovoltaic (PV) systems, are increasingly employed in power systems [1], challenging the flexibility, reliability, power quality, and robustness of grids. The common purpose of energy storage (ES) devices is to improve dynamic performance during large load changes, and provide services such as peak shaving, spinning reserve and strategic loading [2]. As an additional advantage, ES devices in the microgrid with distributed intermittent renewable energy sources can be utilized to maintain voltage, reduce distribution losses, support capacity and defer distribution investment [3].

Variable loads and intermittency of renewable energy sources motivate the introduction of heterogeneous ES devices into DC microgrids [4-5]. Different ES devices have different characteristics and often a single ES device cannot meet all requirements. For example, ultracapacitors can be frequently and efficiently charged/discharged, have high cycle life and limited specific energy, making them suitable to feed high frequency loads. On the contrary, lithium-ion batteries have high specific energy, low specific power, low cycle time and low self-discharge rate, which makes them suitable to supply steady loads [6-7]. Without the help of ultracapacitors feeding the high frequency loads, the batteries have to frequently charge/discharge, affecting their lifetime. Similarly, the ultracapacitors cannot supply energy to steady loads for a long enough time, affecting the power quality. This is the main reason why heterogeneous ES devices are becoming popular in DC microgrids with distributed generation [8-11].

The introduction of ES devices into DC microgrids requires control strategies that prevent the ES devices from prematurely running out of energy, and thus failing to make full use of the capacity of both ES devices and connected renewable resources [4]. Many different approaches to control ES devices in microgrids have been reported in literature, and can be divided into the following categories: droop control, cooperative control and control of heterogeneous ES devices [6].

Two types of droop control have been proposed for DC microgrids: P-V droop control [5, 12], and I-V droop control [13-14]. In the P-V (I-V) droop control, the droop coefficient is selected to regulate the output power (output current) of ES devices in response to load variations. Both standard droop control methods fail to take the energy level of ES devices into consideration. As a result, all ES devices within the microgrid will share the output power. ES devices with low energy levels will run out of energy first, and the remaining ones will be overloaded, causing them to rapidly discharge and prematurely run out of energy. Therefore, the voltage of the DC microgrid cannot be regulated within the required range [5]. Although the weighted droop control enables the ES devices with a low energy level to share less power, the other ES devices with higher energy levels may be overloaded. On the other hand, after all devices reach a low energy level, low power makes it difficult to maintain the voltage of the DC microgrid [6]. In consequence, the droop control on its own is inadequate to control the distributed ES devices.

Distributed cooperative control methods for ES devices in microgrids have been proposed to improve power sharing performance [15-17]. Considering the neighbouring ES device states, the controller manages to regulate the voltage and balance energy. The control system balances the ES devices towards a common energy level while sharing power to loads [5]. However, only homogenous ES devices - batteries were considered. Hence, the batteries suffer from fast charge/discharge rates when loads vary or intermittent renewable energy sources are connected, shortening their lifetime.
Heterogeneous ES devices control strategies were also reported. The impedance [18-19], capacitive [20-21], and multi-agents cooperative control methods [4] enable the high frequency loads to be allocated to the ES devices with faster cycle times. The main advantage of the proposed control strategy over [4] is that no communication is required between the ultracapacitors.

Motivated by the above discussion, this paper proposes a multi-agent distributed cooperative capacitive control for a DC microgrid with distributed heterogeneous ES devices – ultracapacitors and lithium ion batteries.

The proposed control method has the following advantages: 1) the cooperative controller ensures the batteries balance to a common energy level and share power; 2) the high frequency component of loads is supplied by the ultracapacitors; 3) the low frequency component of loads is fed by the batteries; 4) communication links are only needed between neighbouring batteries, not all heterogeneous devices; 5) ultracapacitors are able to feed the high frequency loads connected to other buses. Presented simulation results verify performance of the proposed method under variable loads.

II. DISTRIBUTED HETEROGENEOUS ENERGY STORAGE SYSTEM

The distributed heterogeneous energy system is comprised of DC-DC converters, distributed batteries and ultracapacitors, and loads. Each ES device employs a V-I droop control, and a voltage and inner current PI controller. The batteries supply the low frequency component and the ultracapacitors the high frequency component of loads using a virtual impedance control, rather than a filter. The cooperative control enables the energy levels of batteries to converge to a same level, ensuring that none of the batteries will run out of energy prematurely or over-charge. Fig.1 shows the structure of one heterogeneous ES system. Only islanded operation of the DC microgrid is considered in this paper.

A. Battery

The Unnewehr universal battery model is used [4]. The state of charge (SoC) dynamics and battery voltage of the battery ES system are described by,

\[
\text{SoC} = -\eta \frac{C_s}{C_B} i_{lb}, \quad v_{bat} = E_{bat} - r_{bat} i_{lb} - K_{bat} \text{SoC},
\]

where SoC represents the energy level of the battery; \(E_{bat}\) is the internal battery voltage; \(r_{bat}\) is the internal battery resistance; \(K_{bat}\) is the polarization constant; \(\eta\) is the battery Coulombic efficiency; \(C_s\) is the nominal battery capacity in ampere-seconds; \(v_{bat}\) is the battery output voltage; and \(i_{lb}\) is the battery connected DC-DC converter inductor current.

B. Ultracapacitor

A three-time-constant equivalent circuit model of the ultracapacitor from [22] is adopted, as shown in Fig. 2. The state space model of the ultracapacitor is,

\[
\begin{align*}
\dot{x}_{cap} &= A_{cap} x_{cap} + B_{cap} u + C_{cap} y, \\
\end{align*}
\]

where \(x_{cap}\) is the state vector, \(u\) is the input vector, and \(y\) is the output vector.
\[
\frac{v_{oc}}{v_{oc}} = \frac{H' G_c G_{oc}^H}{1 + H' G_c G_{oc}^H}, \hspace{1cm} (3)
\]

\[
H' = k_{ip} + \frac{k_{ip}}{s}, \hspace{1cm} G_{oc} = \frac{1 + s \cdot r_c C_s}{s \cdot C_s}, \hspace{1cm} G_{oc}^H = \frac{H' G_{oc}}{1 + H' G_{oc}}, \hspace{1cm}
\]

where \(v_{oc}\) is the output voltage reference, \(v_{oc}\) is the local bus voltage of the battery/ultracapacitor system; \(k_{ip}\), and \(k_{ip}\), are the voltage PI controller proportional and integral gains, \(k_{ip}\), and \(k_{ip}\), are inner current PI controller proportional and integral gains; \(C_s\) is the capacitance and \(r_c\) the internal resistance of the output capacitor; \(L_s\) is the inductance and \(r_c\) the internal resistance of the input inductor; subscript \(\bullet\) represents \(b\) for the battery system and \(c\) for the ultracapacitor system respectively.

The virtual impedance based control is implemented for the battery and ultracapacitor. According to [21], by introducing a virtual resistance and capacitance into the battery and ultracapacitor control loop respectively, as shown in Fig. 3, the batteries will respond to the low frequency component and the ultracapacitors to the high frequency component of load.

D. Virtual impedance based control

Compared with the filter-based methods, only two parameters, \(R_{VI}\) and \(C_{VI}\), have to be tuned. The DC-DC converters output voltage references \(v_{oc}\) are generated based on the nominal voltage of the microgrid, \(v_{mg}\), and the virtual impedance feedback voltages as

\[
v_{ob}^* = v_{mg} - R_{VI} \left( i_{ob} - i_{coop}^* \right), \hspace{1cm} (4)
\]

\[
v_{oc}^* = v_{mg} - \frac{1}{C_{VI}} \cdot s \cdot i_{oc} - \delta v^c, \hspace{1cm} (5)
\]

where \(i_{ob}\) and \(i_{oc}\) are the currents injected into the bus from the battery and ultracapacitor systems respectively; \(i_{coop}^*\) is the cooperative control signal; and \(\delta v^c\) is a voltage correction term generated by a local PI controller to maintain the ultracapacitor voltage at the rated value,

\[
\delta v^c = G^c \left( v_{up}^* - v_{up} \right), G^c = k_{ip} + \frac{k_{ip}}{s},
\]

where \(v_{up}\) is the rated ultracapacitor voltage, \(k_{ip}\) and \(k_{ip}\) are the proportional and integral gains, respectively.

E. Cooperative Control

The battery leader is introduced to compensate the voltage deviation caused by the virtual droop control. The battery leader receives the rated microgrid voltage \(v_{mg}\). A PI controller \(H_{lead}^l\) sets the battery current signal \(i_{lead}\) to regulate the battery leader voltage to the microgrid reference. The control system of the battery leader is

\[
i_{lead} = H_{lead}^l \left( v_{mg} - v_{ob} \right), \hspace{1cm} (6)
\]

\[
H_{lead}^l = k_{leadp} + \frac{k_{lead}}{s},
\]

\[
v_{ob}^* = v_{mg} - R_{VI} \left( i_{ob} - i_{lead} \right),
\]

where \(k_{leadp}\) and \(k_{lead}\) are PI controller proportional and integral gains of the leader voltage regulation loop.
For the battery followers, cooperative control modifies the virtual impedance control output voltage signal by introducing the current signal $i_{coop}$, which is governed by the modified voltage regulation control signal and state of charge balancing control signal as [24, 25]

$$i_{coop}^* = H^{SoC} \varepsilon_{SoC} + H^\tau \varepsilon_\tau^*, \quad (7)$$

where $k_{SoC}$ and $k_\tau$ are PI controller proportional and integral gains of the modified voltage regulation loop; $k_{SoC}$ and $k_{SoC}$ are PI controller proportional and integral gains of the state of charge regulation loop; $\varepsilon_{SoC}$ is the neighbourhood state of charge tracking error of each battery, and $\varepsilon_\tau$ is the neighbourhood modified voltage tracking error of each battery.

### III. CONTROL DESIGN

#### A. Virtual Impedance Control

Virtual impedance control parameters are selected based on the desired load crossover frequency, $f$, between the battery and the ultracapacitor [21],

$$f = 1/\tau = 1/(R_{eq}C_{eq}). \quad (8)$$

The virtual resistance is selected so that the ES system will use its full output power capacity to supply loads and extra power for energy balancing [25], $R_{eq} = \frac{\Delta v}{P_{max}/v_{eq}}$, where $\Delta v$ is the maximum allowed deviation of the microgrid voltage, and $P_{max}$ is the maximum output power of the battery. The virtual impedance parameters should be selected before the cooperative control design.

#### B. Cooperative Control

The communication network can be described by a directed graph. An edge $(i, j) \in \mathcal{E}$ if there is a link allowing information to flow from node $i$ to node $j$. Direct communication from the leader to its neighbouring followers is described by the pinning matrix $G = \text{diag}(g)$, where $g_i = 1$ if $(0, i) \in \mathcal{E}$ and $g_i = 0$ otherwise. Let the neighbours of node $i$ be $\mathcal{N}_i$, where $j \in \mathcal{N}_i$ if $(i, j) \in \mathcal{E}$. Let the graph adjacency matrix be

$$A = [a_{ij}] \in \mathbb{R}^{N \times N}, \quad a_{ij} = \begin{cases} 1, & (j, i) \in \mathcal{E} \\ 0, & \text{otherwise} \end{cases}. \quad (9)$$

The graph degree matrix is given by

$$D = \text{diag}(d_i). \quad (10)$$

The graph Laplacian matrix is given by $L = D - A$, [5, 26-27].

In order to unify the states of batteries distributed in the DC microgrid, the control law of each agent must respect the graph topology and can only use the local neighbourhood information of batteries. The neighbourhood state of charge and modified voltage tracking errors of each battery can be defined as

$$\varepsilon_{SoC} = \sum_{j=1}^N a_{ij} (SoC_j - SoC_i) + g_i (SoC_0 - SoC_i), \quad (11)$$

$$\varepsilon_\tau = \sum_{j=1}^N a_{ij} (\bar{v}_j - \bar{v}_i) + g_i (\bar{v}_0 - \bar{v}_i). \quad (12)$$

The voltage regulation signal is modified by introducing the virtual droop resistance into the voltage regulation again, to compensate the voltage deviation of the battery system. Thus the modified voltage signal is given as

$$\bar{v} = v_{eq} + R_{eq}i_{eq}. \quad (13)$$

The cooperative control parameters in (6) and (7) can be chosen to ensure the stability of the cooperative control system [24, 28], and the voltage and current PI controllers parameters can be tuned to guarantee the stability of the battery and ultracapacitor systems.

### IV. CASE STUDY

A simulation has been carried out to demonstrate performance of the proposed control system to balance the energy and to allocate the low and high frequency component of the loads to batteries and ultracapacitors respectively. The simulation was carried out for a six bus islanded DC microgrid shown in Fig 4. Bus 1 to bus 3 and bus 6 are connected to batteries, while the bus 4 and 5 are connected to ultracapacitors. The battery system connected to bus 1 is set as a leader agent, while others are follower agents. Battery systems communicate with their neighbours via a sparse communication network. The communication link is a spanning tree between the battery systems. The DC microgrid
voltage range of 380 V ± 5% is required, according to standards proposed for DC low voltage distribution by the ETSI and Emerge Alliance [5]. Each 7.35kWh lithium-ion battery and 500F ultracapacitor are connected to a bus via a 5kW rated bidirectional DC-DC converter. The buses are connected by 100m of 5.5mm² CU cable modelled as a series RL circuit. The nonlinear averaged model of DC-DC converter with voltage and current control loop validated in [4] was used in the simulation. The initial energy values of the batteries vary between their maximum 100% energy level of 7.35kWh and their minimum 40% energy level of 2.94kWh. All parameters are shown in Table 1.

Initially, a 0.6kW load is connected to each battery and each ultracapacitor bus. At $t = 170$ min, each load increases to 0.9kW and drops to 0.6kW after 30min. At $t = 230$ min, only the load on bus 3 increases to 1.08kW and drops to 0.6kW after 30min. As it can be seen in Fig. 5 (a, c-f), the cooperative control balances the energy levels of all batteries while the batteries share power to supply the low frequency component of the loads. When the loads change, no matter which bus experiences the change, the batteries gradually increase their

<table>
<thead>
<tr>
<th>TABLE I. SIMULATION PARAMETERS</th>
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<tbody>
<tr>
<td><strong>DC Microgrid</strong></td>
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<tr>
<td>$V_{MG}$</td>
</tr>
<tr>
<td><strong>DC-DC Converter, and Voltage &amp; Current Controller</strong></td>
</tr>
<tr>
<td>$L$</td>
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<td>$C$</td>
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<tr>
<td>$k_{cp}$</td>
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<td><strong>Battery System</strong></td>
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<tr>
<td>$E_{bat}$</td>
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<tr>
<td>$\eta$</td>
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<tr>
<td><strong>Ultracapacitor System</strong></td>
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<tr>
<td>$v_{cap}$</td>
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<tr>
<td>$R_f$</td>
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<tr>
<td><strong>Virtual Impedance Parameters</strong></td>
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<tr>
<td>$R_{VT}$</td>
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<tr>
<td>$\Delta v$</td>
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<td><strong>Cooperative Controller</strong></td>
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<tr>
<td>$k_{\tau}$</td>
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<td>$k_{SoC}$</td>
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Fig. 5. Case study results: (a) SoCs of batteries, (b) local bus voltages, (c)-(d) output powers from converters, (e)-(f) currents injected by converters.
output power and eventually share power to supply the load. The virtual impedance control forces the high frequency (transient) component of the loads to the ultracapacitors. After the transients diminish, the ultracapacitors stop supplying power. The bus voltages are maintained within the required range of 380V ± 5%, as shown in Fig. 5(b).

V. CONCLUSION

A distributed multi-agent cooperative control method to balance the energy level of batteries in a DC microgrid with distributed heterogeneous ES devices was proposed. A sparse communication network is required only between the batteries, while the virtual impedance control allocates the high frequency component of the loads to the ultracapacitors and the low frequency component to the batteries. The simple approach offers advantages in terms of robustness, extensibility, and flexibility. Simulation results verified performance of the proposed control strategy for variable loads.

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REFERENCES


