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Resilience-Oriented Control for Cyber-Physical Hybrid Energy Storage Systems Using A Semi-Consensus Scheme: Design and Practice

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Abstract—Hybrid energy storage systems (HESSs) can simultaneously harness the advantages of batteries and supercapacitors (SCs) in various loading situations. Coupled with communication links, cyber-physical HESSs (CPHSs) would be threatened by unexpected cyber attacks that may cause damage to electrical devices and even collapse the entire system. To overcome the adverse impacts of attacks, a resilience control scheme is proposed in this paper. The proposed scheme provides a unified form integrated with adaptive laws to guarantee multi-functional HESS operations, i.e., DC bus voltage restoration, transient current allocation between batteries and SCs, proportional battery current sharing and battery SOC (state of charge) balancing, under cyber attacks. The proposed resilience control allows to establish communication links only among batteries, whereas SCs are free of data exchange process, which can save system capital costs. The stability of the proposed control is proved by Lyapunov stability theory. The effectiveness and feasibility of the proposed approach is validated on a hardware-in-the-loop (HIL) testing platform.

Index Terms—Hybrid energy storage system, semi-consensus strategy, multi-functional operations, cyber attacks resilience control.

I. INTRODUCTION

As a crucial building block of future smart grids, microgrids (MGs) provide an elegant way to incorporate heterogeneous distributed generation (DG) and diverse passive/active loads. [1]. Normally, ever-evolving MGs can be categorized into AC and DC grids. AC MGs inherit the power transformations from conventional power systems and hence, they are compatible with most of existing electrical equipment [2]. However, DC MGs have drawn increasing attention from both academic and industrial realms, due to less energy conversion stages, higher efficiencies, absence of reactive power, and no need for frequency control. Moreover, many modern household appliances,

data centers and LED lights are DC compatible, and therefore, designing DC MGS to serve such systems and applications is of research interest.

Renewable energy sources (RESs) which feature severe fluctuations and intermittencies may jeopardize the operation safety of DC MGs. Energy storages (ESs) should be properly deployed to smooth RES generations and compensate for their uncertainties. However, as explained in [3], there is no single type of ESs that are simultaneously characterized having high power- and energy-density. Specifically, batteries have relatively high energy capacity but limited dynamic responses, whereas supercapacitors (SCs) can output a large amount of power in a short period but they are quickly depleted if not properly regulated. In this situation, hybrid energy storage systems (HESSs) should be constituted to harness the advantages of batteries and SCs. When there is a load change, the low and high frequency components of the change can be allocated to batteries and SCs, thus prolonging overall HESS lifetime.

In general, the energy management of HESSs can be realized by decentralized, centralized and distributed controls. For decentralized methods, no communication is utilized and different ESs have their own local controllers which are blind to the entire system performance. In [4], an extended droop is proposed and applied to SCs. By using the droop, transient load power is spontaneously assigned to SCs. An integral droop (ID) is formed in [2] by mimicking the charging and discharging process of capacitors. Coordinating ID and voltage-power droop in an HESS, dynamic power allocation for batteries and SCs during system transition can be autonomously obtained. Similar results can also be found in [5] where virtual impedance techniques are proposed for dynamic power sharing in HESSs. The authors in [6] propose to equip ESs with self-disciplined stabilizers which endow stable dynamic power decomposition in transit states. Although the decentralized controls are flexible for implementation and may help to boost system reliability, the control methods are provincially applicable to simple system architectures where more advanced HESS functionalities are unattainable.

Benefiting from the vigorous growth in communication technologies, such as WiFi and wired Ethernet, a central controller under the centralized scheme is capable of collecting data over the entire energy storage system, making decisions based on predesigned algorithms and transmitting commands to individual ESs. For example, a SCADA system built by the company Schneider is used in [7] to achieve complex hierarchical control for HESSs. The same communication system is further adopted in [8] to achieve seamless transition between MG

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grid-tied and islanded modes. In [9], model predictive control is programmed in a central controller to determine power references for batteries and SCs. The same idea is reported in [10] where all decisions are made in a centralized fashion. However, as criticized in [11], centralized control mechanisms are vulnerable to single points of failure, which means a failure in a small part of a system can prevent the entire system from correct operation. In addition, a single central controller would suffer from heavy computational burdens as it needs to collect, process and transmit all data across the entire MG.

Different from the centralized controls, distributed control schemes allow ESs in HESSs to communicate with their neighbors. In this way, the computational burden in central controllers can be naturally distributed to multiple controllers, thus improving system reliability and scalability. There are hitherto numerous distributed control methods reported in the literature for MG applications. In [12], a distributed secondary controller is designed to restore the DC MG bus voltage. The controller is further generalized for hybrid AC/DC MGs to achieve proportional power sharing among interlinking converters [13]. A distributed cooperative coordination for HESSs is studied in [14] where both current sharing and state of charge (SOC) balancing can be obtained. In [15], a semi-consensus strategy which is based on the linear multi-agent theory is proposed to realize HESS multi-functional operations. A virtual voltage drop is generated by a well-devised distributed controller to ensure both current sharing and voltage restoration [16]. Similar results are also achieved by [17] where a distributed hybrid secondary control is proposed, considering discrete-time interaction which can reduce local controller computations. In [18], event-trigger concepts are merged into distributed controllers for mitigating communication intensities in DC MG systems.

In fact, as elaborated in [19], the HESS having a physical configuration, together with its communication layer, inherently constitutes a cyber-physical system, as shown in Fig. 1. For cyber-physical HESSs (CPHSs), the security in the cyber level is of high importance. If a cyber attack is not clearly perceived and timely addressed, erratic control commands incurred in the communication network will result in abnormal behaviors of electrical hardware and eventually disrupt the whole system. For instance, an illegal attacker hacked into the control center of a Ukrainian distribution grid in 2015, causing wide-area service outages and huge economic losses [20]. Despite this fact, however, the aforementioned distributed controls simply assume the HESS is well protected; they do not take into account the situation where the HESS cyber network is under attack. To overcome this difficulty and guarantee the HESS operating safety, a resilience controller is proposed which helps to strengthen the system resilience against the attacks on distributed controllers themselves. The main merits of the proposed control can be summarized as follows:

- 1) The proposed resilience control provides a unified form that can be applied to achieve both voltage recovery of the critical DC bus in HESS and current sharing/SOC balancing among batteries, which yields easy practical implementations.
- 2) Even in the case of cyber attacks, the proposed control enables to reserve the autonomous transient power allocation between batteries and SCs, i.e., batteries compensate for the low frequency components of load power and SCs handle high frequency ones during transient states.
- 3) The proposed control is novelly integrated with an

Fig. 1. A conceptual cyber-physical system.

Fig. 2. Typical schematic of a cyber-physical hybrid energy storage system, where $P_{Bj}(j = 1, \dots, m)$ and $V_{Bj}(j = 1, \dots, m)$ are the power exchange between the corresponding battery # j and the entire network, and the bus voltage, respectively, V_b is the critical DC bus voltage, $P_{SCj}(j = 1, \dots, n)$ is the power exchanged between the DC bus and the corresponding SC # j , and P_L is the load power.

adaptive law that can estimate the bounds for the attacks. The estimations are then used to update control gains of the resilience control in real time. By this mean, the impact of cyber attacks on overall HESS dynamics can be largely suppressed, thus enhancing the resilience and safety of the entire CPHSs.

4) For the HESS with the resilience control, only batteries have communication links whereas SCs do not exchange information with any other ESs, which is termed as semi-consensus scheme. Thanks to this scheme, the capital costs of constructing the communication network would be substantially saved, and SCs are naturally exempted from cyber attacks.

The rest of this paper is organized as follows. Section II illustrates the system architecture and problem formulation. Section III provides the detailed design of the proposed resilience control strategy. Parameter selections and controller verifications are given in Sections IV and V, respectively. Finally, Section VI concludes this paper.

II. SYSTEM DESCRIPTION AND PROBLEM FORMULATION

A. Cyber-Physical Hybrid Energy Storage System

Fig. 2 shows the typical architecture of a CPHS where SCs are excluded from the cyber layer, so as to save system investment costs. As seen in Fig. 2, the ESs are interlinked via a complex impedance network, considering practical applications. Specifically, there are totally m batteries and n SCs. As entities with comparatively high energy-densities, batteries could be placed at any desired location and each battery is connected to its local bus (V_{Bi} , $i = 1, \dots, m$) via a bidirectional DC/DC converter. Since there is a critical bus (V_b) to which many significant loads are connected, to ensure the power and voltage qualities, the SCs should be directly coupled to the critical bus by power converters. Hence, the line impedances between SCs and the critical bus would be very small and can be neglected. It is worth noting that P_L , as explained in [21], stands for the equivalent load incorporating constant power loads (CPLs), P_{CPLs} , constant power sources (CPSs),

Fig. 3. Boost converter and the control of ES: (a) for the j th SC and (b) for the j th battery.

P_{CPSs} , and resistive loads (RLs), P_{RLs} . CPLs normally refer to motor drives or electronic loads with tight regulations, and CPSs emulate RES generations such as PVs and wind turbines. In this regard, P_L can be written as the following,

$$P_L(t) = P_{CPLs}(t) + P_{RLs}(t) - P_{CPSs}(t). \quad (1)$$

Generally, different ESs may have distinct terminal voltages which would be comparatively low. For a DC system with a specified voltage level, it is not always possible to stack up multiple ESs to reach the desired level, but boost converters can be employed to flexibly bridge the ESs and the DC system. In Fig. 2, batteries and SCs are interfaced with their respective boost converters, which are interpreted in Fig. 3.

Considering that SCs are installed close to the critical bus, as seen from Fig. 3(a), the SC boost converters are operated in voltage regulation modes. Then, the SCs can cooperatively control the critical bus. The parameter design of the proportional-integral (PI) controllers for boost converters has been clearly given in [2] with v_{rj} being the SC voltage reference generated by a droop equation and can be described as

$$v_{rj} = V_{th} - R_j \left(\frac{\omega}{s + \omega} \right) i_{oSCj}, \quad (2)$$

where i_{oSCj} denotes the output current of the j th SC converter, V_{th} , R_j and ω stand for the normal bus voltage, the virtual resistance and the crossover frequency of low pass filter (LPF). The LPF would help to smooth the measured SC output current, and it also contributes virtual inertia to the critical DC bus, as apprehended from [22]. Since v_{rj} equals V_b , it is possible to realize current sharing among SCs by (2), i.e.,

$$i_{oSC1} : i_{oSC2} : \dots : i_{oSCn} = R_1^{-1} : R_2^{-1} : \dots : R_n^{-1}. \quad (3)$$

Similar to the power sharing pattern in [3], it is seen from (3) that the output currents of SC-interfaced converters are inversely proportional to their corresponding virtual resistances R_j . By carefully designing R_j , the SC with larger capacitance will supply more power, and vice versa.

For the complex impedance network that couples dissimilar ESs, the critical bus with SCs acts as a slack terminal, whereas other buses including V_{Bj} , $j = 1, \dots, m$ can be functioning in power control modes so as not to induce underlying voltage regulation conflicts. In this sense, as shown in Fig. 3(b), only a PI for the inductor current regulation is adopted. The converter output voltage V_{Bj} will be autonomously driven to a particular level when the power flow across the entire impedance network is determined. i_{rj} is the current reference generated by the distributed controller involving cyber communications. The critical bus voltage restoration and current sharing/SOC balancing of batteries are mathematically modeled in the subsequent section. Upon the models, the resilience controller will be proposed and tested on a cyber-physical platform.

B. Problem Formulation

As explicated in Figs. 2-3 and (3), the droop characteristics assigned to SCs would unavoidably induce V_b to deviate from V_{th} , thus possibly impairing DC system voltage qualities. Moreover, SCs featuring fast dynamics may not meet the requirements of continuous power generation required by P_L . Driven by these problems, we could introduce a dynamic to V_b , i.e., let

$$\dot{V}_b = u_v, \quad (4)$$

where u_v represents the virtual control law to regulate V_b . The error e_v between the real time V_b and its nominal voltage V_{th} has the following dynamic:

$$\dot{e}_v = \dot{V}_b - \dot{V}_{th} = u_v. \quad (5)$$

It is worth mentioning that (5) is indeed in the cyber layer, which might be exposed to cyber attacks. When attacks take place, u_v would lose a part of its effectiveness and is entangled with a superposition [23]. These phenomena can be appositely modeled in a mathematical way by introducing ϕ_v and δ_v , and (5) can be further updated as

$$\dot{e}_v = \phi_v u_v + \delta_v, \quad (6)$$

where ϕ_v denotes an effectiveness-losing factor and δ_v is an unknown time-varying superposition. To more easily construct the resilience control, (6) can be rearranged into a standard state space model as in [23]:

$$\dot{e}_v = A_v e_v + B_v (\phi_v u_v + \delta_v) \quad (7)$$

in which $A_v = 0$ and $B_v = 1$ are system matrices.

As for batteries, their output currents i_{Bj} , $j = 1, 2, \dots, m$, should be proportional to the individual ratings, $\bar{C}_{Bjs}$, and battery SOC should be balanced. The instantaneous SOC of the j th battery is defined as

$$\text{SOC}_{Bj} = \text{SOC}_{Bj0} - \int \frac{i_{Bj}}{3600\bar{C}_{Bj}} dt, \quad (8)$$

where SOC_{Bj0} is the initial SOC value. To realize the aforesaid two control objectives for batteries, the following dynamic equations can be formulated by differentiating (8) and performing the feedback linearization as in (4),

$$\begin{aligned} \dot{\text{SOC}}_{Bj} &= -i_{Bj}/(3600\bar{C}_{Bj}), \\ \dot{i}_{Bj} &= u_{Bj}, \end{aligned} \quad (9)$$

where u_{Bj} is a virtual control input to regulate battery current. To flexibly set the inductor current reference, (9) can subsequently be mapped into a new state space where the two states SOC_{Bj} and i_{Bj} are replaced by $x_{j1} = 3600\text{SOC}_{Bj}$ and $x_{j2} = -i_{Bj}/\bar{C}_{Bj}$, respectively. Computing the time derivatives of x_{j1} and x_{j2} gives

$$\begin{aligned} \dot{x}_{j1} &= x_{j2}, \\ \dot{x}_{j2} &= u_j, \end{aligned} \quad (10)$$

where $u_j = -u_{Bj}/\bar{C}_{Bj}$ is the input signal for the second-order integral chain system in the j th battery. Similar to (6), an effectiveness-losing factor ϕ_{jE} and an unknown time-varying superposition δ_{jE} are accordingly imposed to u_j to give

$$\dot{x}_j = A_E x_j + B_E (\phi_{jE} u_j + \delta_{jE}), \quad (11)$$

where $x_j = [x_{j1} \ x_{j2}]^T$, $A_E = [0 \ 1; 0 \ 0]$, and $B_E = [0 \ 1]^T$.

Note that ϕ_v , ϕ_{jE} , δ_v , δ_{jE} are the actual signals existing in closed-loop control systems. It is thus possible to assume these

signals are bounded, i.e., $0 < \underline{\phi}_v \leq \phi_v < 1$, $0 < \underline{\phi}_{jE} \leq \phi_{jE} < 1$, $\|\delta_v\| \leq \bar{\delta}_v$, and $\|\delta_{jE}\| \leq \bar{\delta}_{jE}$. The quantities $\underline{\phi}_v$, $\underline{\phi}_{jE}$, $\bar{\delta}_v$, and $\bar{\delta}_{jE}$ are unknown constants. Note that the supercapacitor only uses the droop controller as in 2, and there is no chance to execute cyber attacks to the supercapacitor as in (7) and (11). Hence, the supercapacitor could be exempted from the attacks.

III. RESILIENCE CONTROL DESIGN

For the systems (7) and (11) undergoing cyber attacks, the control objectives can be formulated as follows: 1) the voltage of the critical DC bus should be restored to its nominal value, i.e., $\lim_{t \rightarrow \infty} e_v = 0$; 2) SOC balancing and proportional current sharing among batteries should be realized, i.e., $\lim_{t \rightarrow \infty} (x_{j1} - x_{1ref}) = 0$ and $\lim_{t \rightarrow \infty} (x_{j2} - x_{2ref}) = 0$, $j = 1, 2, \dots, m$, where x_{1ref} and x_{2ref} stand for the reference SOC value and normalized reference current, respectively, and are given as,

$$x_{1ref} = \frac{3600}{m} \sum_{j=1}^m \text{SOC}_{Bj0} + \int x_{2ref} dt, \quad (12)$$

$$x_{2ref} = I_{ref}$$

where I_{ref} is a constant, SOC_{j0} is the initial SOC of the j th battery. As known from [2] and the control theory, the voltage control error e_v in (7) can be viewed as an indicator of the power imbalance on DC bus, i.e., larger e_v suggests batteries should output more current/power to compensate for the load demand. Inheriting this idea, a cascaded control scheme can be formulated where (10) and (4) are the plants of inner and outer control loops, respectively. I_{ref} in (12) is defined as $\frac{-\int u_v dt}{\sum_{j=1}^m C_{Bj}}$. It is then possible to tune the dynamics of the inner control loop to be much faster than the outer, such that the dynamic decoupling of the two systems is achieved and I_{ref} can be regarded as a constant when designing the resilience controller.

Let $x_{ref} = [x_{1ref} \ x_{2ref}]^T$ and its dynamic can be given as,

$$\dot{x}_{ref} = A_E x_{ref}. \quad (13)$$

The time derivative of error vector $e_j = x_j - x_{ref}$ is obtained as

$$\dot{e}_j = A_E e_j + B_E (\phi_{jE} u_{jE} + \delta_{jE}). \quad (14)$$

A. Controller Design of Unified Form

It should be mentioned that, despite different orders, the error dynamics depicted in (7) and (14) share a standardized mathematical format. This fact facilitates the design of a unified resilience controller that could be applied to (7) and (14) to resist cyber attacks on control inputs. The proposed controller of unified form is given as

$$\text{for (7): } u_v = -\hat{a}_v \frac{B_v^T P_v \varepsilon_v}{\|B_v^T P_v \varepsilon_v\|} - \hat{b}_v B_v^T P_v \varepsilon_v, \quad (15a)$$

$$\text{for (14): } u_{jE} = -\hat{a}_{jE} \frac{B_E^T M P_E \varepsilon_{jE}}{\|B_E^T M P_E \varepsilon_{jE}\|} - \hat{b}_{jE} B_E^T M P_E \varepsilon_{jE}, \quad (15b)$$

where P_v and P_E are positive definite matrices that will be explained in the subsequent context. In (15a), the control input u_v intends to restore the DC bus voltage to its nominal value. $M = \text{diag}([\gamma_E \ 1])$, $\gamma_E > 0$ can be used to adjust the dynamics of SOC balancing. $\varepsilon_v = \gamma_v e_v$, $\gamma_v > 0$ is an auxiliary variable,

whereas $\hat{a}_v$ and $\hat{b}_v$ are time-varying control gains governed by a novel adaptive law (Adaptive Law I).

Adaptive law I:

$$\dot{\hat{a}}_v = \mu_{v1} \|B_v^T P_v \varepsilon_v\| - \mu_{v2} (\hat{a}_v - \hat{c}_v), \quad (16a)$$

$$\dot{\hat{c}}_v = \mu_{v3} (\hat{a}_v - \hat{c}_v), \quad \hat{a}_v|_{t=0} > \hat{c}_v|_{t=0} > 0, \quad (16b)$$

$$\dot{\hat{b}}_v = \mu_{v4} \|B_v^T P_v \varepsilon_v\|^2 - \mu_{v5} (\hat{b}_v - \hat{d}_v), \quad (16c)$$

$$\dot{\hat{d}}_v = \mu_{v6} (\hat{b}_v - \hat{d}_v), \quad \hat{b}_v|_{t=0} > \hat{d}_v|_{t=0} > 0, \quad (16d)$$

in which $\mu_{v1}, \dots, \mu_{v6}$ are positive constants. $\hat{a}_v$ and $\hat{b}_v$ are able to perceive the values relating to the bounds of attacks, and help to suppress the attack impacts on bus voltage restoration. Different from (7), (14) represents the dynamics of the j th battery system. To attain battery SOC balancing and proportional current sharing, m battery systems should exchange information among one another via communication links. In this sense, the formulation of e_{jE} would slightly differ from e_v and can be computed as

$$\varepsilon_{jE} = M \sum_{k=1}^m a_{jk} (x_j - x_k) + g_j (x_j - x_{ref}), \quad (17)$$

with $a_{jk} = 1$ if the k th battery has a communication link to the j th battery; otherwise, $a_{jk} = 0$, and g_j is a pinning gain which equals 1 if the j th battery is allowed for accessing x_{ref} . Then, similar to (16), $\hat{a}_{jE}$ and $\hat{b}_{jE}$ in (15b) can be calculated according to Adaptive Law II,

Adaptive law II:

$$\dot{\hat{a}}_{jE} = \mu_{jE1} \|B_E^T M P_E \varepsilon_{jE}\| - \mu_{jE2} (\hat{a}_{jE} - \hat{c}_{jE}), \quad (18a)$$

$$\dot{\hat{c}}_{jE} = \mu_{jE3} (\hat{a}_{jE} - \hat{c}_{jE}), \quad \hat{a}_{jE}|_{t=0} > \hat{c}_{jE}|_{t=0} > 0, \quad (18b)$$

$$\dot{\hat{b}}_{jE} = \mu_{jE4} \|B_E^T M P_E \varepsilon_{jE}\|^2 - \mu_{jE5} (\hat{b}_{jE} - \hat{d}_{jE}), \quad (18c)$$

$$\dot{\hat{d}}_{jE} = \mu_{jE6} (\hat{b}_{jE} - \hat{d}_{jE}), \quad \hat{b}_{jE}|_{t=0} > \hat{d}_{jE}|_{t=0} > 0, \quad (18d)$$

where $\mu_{jE1}, \dots, \mu_{jE6}$ are positive constants.

B. Stability Analysis

To show that the proposed resilience controller described by (15) can correctly restore the DC bus voltage, balance the SOC of different batteries, and enable proportional current sharing, a stability analysis in time domain by using Lyapunov techniques is performed in detail as follows.

Select a collective Lyapunov function:

$$U = \frac{1}{2} \bar{e}^T ((L + G) \otimes M P_E M) \bar{e} + \frac{1}{2} e_v^T \gamma_v P_v e_v + \frac{1}{2} \sum_{j=1}^m \frac{\phi_{jE}}{\mu_{jE1}} \tilde{a}_{jE}^2 + \frac{1}{2} \sum_{j=1}^m \frac{\phi_{jE}}{\mu_{jE4}} \tilde{b}_{jE}^2 + \frac{1}{2} \sum_{j=1}^m \frac{\phi_{jE} \mu_{jE2}}{\mu_{jE1} \mu_{jE3}} \tilde{c}_{jE}^2 + \frac{1}{2} \sum_{j=1}^m \frac{\phi_{jE} \mu_{jE5}}{\mu_{jE4} \mu_{jE6}} \tilde{d}_{jE}^2 + \frac{1}{2} \frac{\phi_v}{\mu_{v1}} \tilde{a}_v^2 + \frac{1}{2} \frac{\phi_v}{\mu_{v4}} \tilde{b}_v^2 + \frac{1}{2} \frac{\phi_v \mu_{v2}}{\mu_{v1} \mu_{v3}} \tilde{c}_v^2 + \frac{1}{2} \frac{\phi_v \mu_{v5}}{\mu_{v4} \mu_{v6}} \tilde{d}_v^2 \quad (19)$$

where $\tilde{a}_{jE} = \hat{a}_{jE} - \frac{\bar{\delta}_{jE}}{\phi_{jE}}$, $\tilde{b}_{jE} = \hat{b}_{jE} - \frac{c}{\phi_{jE}}$, $\tilde{c}_{jE} = \hat{c}_{jE} - \frac{\bar{\delta}_{jE}}{\phi_{jE}}$, $\tilde{d}_{jE} = \hat{d}_{jE} - \frac{c}{\phi_{jE}}$, $\tilde{a}_v = \hat{a}_v - \frac{\bar{\delta}_v}{\phi_v}$, $\tilde{b}_v = \hat{b}_v - \frac{1}{\phi_v}$, $\tilde{c}_v = \hat{c}_v - \frac{\bar{\delta}_v}{\phi_v}$, and $\tilde{d}_v = \hat{d}_v - \frac{1}{\phi_v}$. $\bar{e} = [e_1^T \ e_2^T \ \dots \ e_m^T]^T$ is

a complete tracking error vector for m battery systems. L and $G = \text{diag}\{g_1 \ g_2 \ \dots \ g_m\}$ denote the Laplacian matrix of the communication network over batteries and pinning matrix, respectively. c is larger than $1/\lambda$ where λ is the smallest non-zero eigenvalue of matrix $L + G$ [24]. It is easy to verify that $\bar{\varepsilon}_E = ((L + G) \otimes M)\bar{e}$ where $\bar{\varepsilon}_E = [\varepsilon_{1E}^\top \ \varepsilon_{2E}^\top \ \dots \ \varepsilon_{mE}^\top]^\top$, $\bar{\varepsilon}_E^\top (I \otimes MPMB_E B_E^\top MPM) \bar{\varepsilon}_E = \sum_{j=1}^m \varepsilon_{jE}^\top PMB_E B_E^\top MP \varepsilon_{jE}$ and $c(L + G)^2 \geq (L + G)$. Substituting these expressions as well as (15a) and (15b) into the time derivative of U gives

$$\begin{aligned} \dot{U} \leq & \Xi_1 + \Xi_2 - \sum_{j=1}^m \phi_{jE} \hat{a}_{jE} \|\varepsilon_{jE}^\top P_E M B_{jE}\| + \sum_{j=1}^m \varepsilon_{jE}^\top P_E M B_{jE} \delta_{jE} \\ & - \sum_{j=1}^m (\phi_{jE} \hat{b}_{jE} - c) \|\varepsilon_{jE}^\top P M B_{jE}\|^2 - \phi_v \hat{a}_v \|\varepsilon_v^\top P_v B_v\| \\ & + \varepsilon_v^\top P_v B_v \delta_v - (\phi_v \hat{b}_v - 1) \|\varepsilon_v^\top P_v B_v\|^2 + \sum_{j=1}^m \frac{\phi_{jE}}{\mu_{jE1}} \tilde{a}_{jE} \dot{\hat{a}}_{jE} \\ & + \sum_{j=1}^m \frac{\phi_{jE}}{\mu_{jE4}} \tilde{b}_{jE} \dot{\hat{b}}_{jE} + \sum_{j=1}^m \frac{\phi_{jE} \mu_{jE2}}{\mu_{jE1} \mu_{jE3}} \tilde{c}_{jE} \dot{\hat{c}}_{jE} + \sum_{j=1}^m \frac{\phi_{jE} \mu_{jE5}}{\mu_{jE4} \mu_{jE6}} \tilde{d}_{jE} \dot{\hat{d}}_{jE} \\ & + \frac{\phi_v}{\mu_{v1}} \tilde{a}_v \dot{\hat{a}}_v + \frac{\phi_v}{\mu_{v4}} \tilde{b}_v \dot{\hat{b}}_v + \frac{\phi_v \mu_{v2}}{\mu_{v1} \mu_{v3}} \tilde{c}_v \dot{\hat{c}}_v + \frac{\phi_v \mu_{v5}}{\mu_{v4} \mu_{v6}} \tilde{d}_v \dot{\hat{d}}_v \end{aligned} \quad (20)$$

In (20), Ξ_1 and Ξ_2 are given as,

$$\Xi_1 = \frac{1}{2} \bar{e}^\top ((L + G) \otimes (MP_E M A_E + A_E^\top M P_E M - 2MP_E M B_E B_E^\top M P_E M)) \bar{e} \quad (21)$$

$$\Xi_2 = -e_v^\top \gamma_v P_v B_v B_v^\top P_v \gamma_v e_v \quad (22)$$

It is worth clarifying that P_E could be found by solving an algebraic Riccati equation, i.e.,

$$MP_E M A_E + A_E^\top M P_E M - 2MP_E M B_E B_E^\top M P_E M = -2Q_E, \quad (23)$$

where Q_E is positive definite. It is also possible to identify P_v by enforcing $-\gamma_v P_v B_v B_v^\top P_v \gamma_v = -Q_v$. Since γ_v , P_v , and B_v are scalars, Q_v should be set as a positive constant, and then $P_v = \sqrt{Q_v}/(B_v \gamma_v)$. By virtue of Lemma in Appendix, $L + G$ is positive definite, and the Kronecker product of $L + G$ and G remains as a positive definite matrix. Then, the following equations hold,

$$\Xi_1 = -\bar{e}^\top ((L + G) \otimes Q_E) \bar{e} \leq 0, \quad (24)$$

$$\Xi_2 = -e_v^\top Q_v e_v \leq 0, \quad (25)$$

The items $\sum_{j=1}^m \varepsilon_{jE}^\top P_E M B_{jE} \delta_{jE}$ and $\varepsilon_v^\top P_v B_v \delta_v$ in (20) can be manipulated:

$$\begin{aligned} \sum_{j=1}^m \varepsilon_{jE}^\top P_E M B_{jE} \delta_{jE} & \leq \sum_{j=1}^m \|\varepsilon_{jE}^\top P_E M B_{jE}\| \|\delta_{jE}\| \\ & \leq \sum_{j=1}^m \|\varepsilon_{jE}^\top P_E M B_{jE}\| \bar{\delta}_{jE} \end{aligned} \quad (26)$$

$$\begin{aligned} \varepsilon_v^\top P_v B_v \delta_v & \leq \|\varepsilon_v^\top P_v B_v\| \|\delta_v\| \\ & \leq \|\varepsilon_v^\top P_v B_v\| \bar{\delta}_v \end{aligned} \quad (27)$$

Substituting (16), (18), and (24)-(27) into (20), and further to make some arrangements result in,

$$\begin{aligned} \dot{U} \leq & \Xi_1 + \Xi_2 - \sum_{j=1}^m \phi_{jE} (\hat{a}_{jE} - \frac{\bar{\delta}_{jE}}{\phi_{jE}}) \|\varepsilon_{jE}^\top P_E M B_{jE}\| \\ & - \sum_{j=1}^m \phi_{jE} (\hat{b}_{jE} - \frac{c}{\phi_{jE}}) \|\varepsilon_{jE}^\top P M B_{jE}\|^2 \\ & - \phi_v (\hat{a}_v - \frac{\bar{\delta}_v}{\phi_v}) \|\varepsilon_v^\top P_v B_v\| \\ & - \phi_v (\hat{b}_v - \frac{1}{\phi_v}) \|\varepsilon_v^\top P_v B_v\|^2 + \sum_{j=1}^m \frac{\phi_{jE}}{\mu_{jE1}} \tilde{a}_{jE} \dot{\hat{a}}_{jE} \\ & + \sum_{j=1}^m \frac{\phi_{jE}}{\mu_{jE4}} \tilde{b}_{jE} \dot{\hat{b}}_{jE} + \sum_{j=1}^m \frac{\phi_{jE} \mu_{jE2}}{\mu_{jE1} \mu_{jE3}} \tilde{c}_{jE} \dot{\hat{c}}_{jE} \\ & + \sum_{j=1}^m \frac{\phi_{jE} \mu_{jE5}}{\mu_{jE4} \mu_{jE6}} \tilde{d}_{jE} \dot{\hat{d}}_{jE} + \frac{\phi_v}{\mu_{v1}} \tilde{a}_v \dot{\hat{a}}_v \\ & + \frac{\phi_v}{\mu_{v4}} \tilde{b}_v \dot{\hat{b}}_v + \frac{\phi_v \mu_{v2}}{\mu_{v1} \mu_{v3}} \tilde{c}_v \dot{\hat{c}}_v + \frac{\phi_v \mu_{v5}}{\mu_{v4} \mu_{v6}} \tilde{d}_v \dot{\hat{d}}_v \end{aligned} \quad (28)$$

Making slight arrangements on (28) leads to

$$\begin{aligned} \dot{U} \leq & \Xi_1 + \Xi_2 - \frac{\phi_v \mu_{v2}}{\mu_{v1}} (\hat{a}_v - \hat{c}_v)^2 - \frac{\phi_v \mu_{v5}}{\mu_{v4}} (\hat{b}_v - \hat{d}_v)^2 \\ & - \sum_{j=1}^m \frac{\phi_{jE} \mu_{jE2}}{\mu_{jE1}} (\hat{a}_{jE} - \hat{c}_{jE})^2 - \sum_{j=1}^m \frac{\phi_{jE} \mu_{jE5}}{\mu_{jE4}} (\hat{b}_{jE} - \hat{d}_{jE})^2 \\ & \leq 0 \end{aligned} \quad (29)$$

From (29), we know that U is bounded. Note that $\dot{U} \equiv 0$ implies that $\Xi_1 = 0$ and $\Xi_2 = 0$. According to the definition of Ξ_1 and Ξ_2 in (24) and (25), we know that $\dot{U} \equiv 0$ implies $\bar{e} = 0$ and $e_v = 0$. Hence, by LaSalle's Invariance principle [25], it follows that the errors $\bar{e}$ and e_v asymptotically converge to zero. Specifically, $\lim_{t \rightarrow \infty} e_v = 0$ indicates the DC bus voltage V_b will be recovered to V_{th} . The vectors x_{jE} s for all batteries will track the reference signal x_{ref} , that is, for any $k, j = 1, 2, \dots, m$,

$$\begin{aligned} \lim_{t \rightarrow \infty} (x_{k1}(t) - x_{j1}(t)) & = 0, \\ \Rightarrow \lim_{t \rightarrow \infty} (\text{SOC}_{Bk}(t) - \text{SOC}_{Bj}(t)) & = 0, \end{aligned} \quad (30)$$

$$\begin{aligned} \lim_{t \rightarrow \infty} (x_{k2}(t) - x_{j2}(t)) & = 0, \\ \Rightarrow \lim_{t \rightarrow \infty} (\frac{i_{Bk}}{\bar{C}_{Bk}} - \frac{i_{Bj}}{\bar{C}_{Bj}}) & = 0. \end{aligned} \quad (31)$$

It is obvious from the above two expressions that SOC balancing and proportional current sharing among batteries could be perfectly achieved by the proposed resilience controller even in the case of cyber attacks. It is worth noting that the above stability analyses are in no relation to the topology of impedance network, line impedance value, renewable generations and loading type. This means the proposed resilience controller will not be affected by power converter level structures, and can be generalized to other DC system, large-scale microgrid system, and any types of hybridization of energy storages without compromising performance at all.

IV. PARAMETER SETTINGS

A. Controller Parameter Settings

The complete diagram of the proposed resilience controller has been illustrated in Fig. 4. The PI controller designs have

Fig. 4. Complete control diagram of the proposed resilience controls for cyber-physical hybrid energy storage system (CPHS). (a) Control diagram of DC bus voltage restoration; (b) Control diagram of the j th battery for proportional current sharing and SOC balancing; (c) Control diagram of supercapacitor-interfaced converter; (d) Control diagram of battery-interfaced converter;

Fig. 5. One-line diagram of the investigated CPHS.

been well explicated in [2], and they are not planned here to avoid replications. It is critical to pinpoint that, as previously mentioned, the decay of $\bar{e}$ is supposed to be far faster than that of e_v . To this end, Q_E in (24) could be carefully selected such that the minimum eigenvalue of $(L + G) \otimes Q_E$ is much larger than the maximum eigenvalue of Q_v . Note that Q_v is a scalar. For simplicity, Q_v is assigned as $1e-8$ and its maximum eigenvalue $\lambda_{max}^{Q_v}$ is certainly $1e-8$. γ_v is chosen 0.01 and P_v in (15a) can accordingly calculated as 0.01. By employing Lemma in Appendix, the following inequality is attained,

$$-(L + G) \otimes Q_E \leq -(\lambda_1 I_{m \times m}) \otimes Q_E. \quad (32)$$

With (32), (24) evolves into

$$\Xi_1 \leq -\bar{e}^T ((\lambda_1 I_{m \times m}) \otimes Q_E) \bar{e} = -\sum_{j=1}^m e_j^T (\lambda_1 Q_E) e_j. \quad (33)$$

Let $\lambda_{min}^{Q_E}$ be the minimum eigenvalue of Q_E , we have the subsequent derivation:

$$-\lambda_1 Q_E \leq -\lambda_1 \lambda_{min}^{Q_E} I_{2 \times 2} \leq -K \lambda_{max}^{Q_v} I_{2 \times 2}, \quad (34)$$

where K is a positive constant scheduled as $2e5$. Then, one can update (34) into a brief form as

$$Q_E \geq \frac{K \lambda_{max}^{Q_v}}{\lambda_1} I_{2 \times 2}. \quad (35)$$

The single-line diagram of the investigated CPHS in this paper is displayed in Fig. 5. The CPHS includes one SC and

totally three batteries with communication infrastructure. Only battery #1 can access x_{ref} . Note that the SC does not involve any data exchange process, thus saving the system capital costs. Therefore, the Laplacian matrix L can be identified as $L = [1, -1, 0; -1, 2, -1; 0, -1, 1]$, and $G = \text{diag}([1, 0, 0])$. It is then easy to find the minimum eigenvalue of $L + G$, i.e., $\lambda_1 = 0.198$. Substituting $K = 2e5$ and λ_1 into (35), Q_E is determined as $10.1 I_{2 \times 2}$. γ_E in M is assigned as 0.02. Returning to (23), with already knowing M , A_E , B_E , and Q_E , the Riccati equation can be resolved by calling the MATLAB command of *icare*, and P_E is computed as

$$P_E = \begin{bmatrix} 167.1242 & 5.0252 \\ 5.0252 & 0.3326 \end{bmatrix} \quad (36)$$

B. Adaptive Law Parameter Settings

It could be observed from (29) that the Lyapunov function U would only stop decreasing when all the quadratic terms on the right hand side of (29) converge to zero. As aforementioned, the decreases of Ξ_1 and Ξ_2 are mainly dominated by Q_v and Q_E , respectively. The rest quadratic terms $(\hat{a}_v - \hat{c}_v)^2$, $(\hat{b}_v - \hat{d}_v)^2$, $(\hat{a}_{jE} - \hat{c}_{jE})^2$, and $(\hat{b}_{jE} - \hat{d}_{jE})^2$, $j = 1, 2, \dots, m$, are governed by (16) and (18). Subtracting (16b) from (16a) gives

$$\dot{\hat{a}}_v - \dot{\hat{c}}_v = \mu_{v1} \|B_v^T P_v \varepsilon_v\| - (\mu_{v2} + \mu_{v3})(\hat{a}_v - \hat{c}_v) \quad (37)$$

Note that $\mu_{v1} \|B_v^T P_v \varepsilon_v\|$ is a positive value and $\hat{a}_v|_{t=0} - \hat{c}_v|_{t=0} > 0$. The dynamic of $\hat{a}_v - \hat{c}_v$ fully depends on $-(\mu_{v2} + \mu_{v3})$ which is the eigenvalue of the characteristic function of (37), and $\hat{a}_v - \hat{c}_v$ always keeps being positive. Due to the fact that adaptive laws provide control parameters to controllers in (15), the dynamic of $\hat{a}_v - \hat{c}_v$ is expected to be much faster than ε_v . To this end, μ_{v2} and μ_{v3} can be assigned with the same value of 250. Then, $\mu_{v2} + \mu_{v3}$ equals 500 which is far larger than $Q_v = 1e-8$, whereas μ_{v1} is set as 1 for simplicity. Similar analyses also apply to (16c-d) and (18), i.e., $\mu_{v5} = \mu_{v6} = 250$, $\mu_{v4} = 1$, $\mu_{jE2} = \mu_{jE3} = \mu_{jE5} = \mu_{jE6} = 250$, and $\mu_{jE1} = \mu_{jE4} = 1$. It can be certainly verified that these configurations still satisfy the requirement that the dynamics of $\hat{b}_v - \hat{d}_v$, $\hat{a}_{jE} - \hat{c}_{jE}$, and $\hat{b}_{jE} - \hat{d}_{jE}$ are faster than ε_v and ε_{jE} .

The parameter settings for the controllers in (15) and the adaptive laws as well as the necessary parameters in Fig. 3 have been summarized in TABLE I.

V. DISCUSSIONS

A. Impact of ω of (2) on DC Bus Stability

A small ω in (2) is to enhance capacitive effects of the DC bus and increase the bus inertia. However, according the stability modeling and eigenvalue analyses for a superpacacitor-interfaced boost converter regulated by (2) feeding a pure CPL, the stability margin of DC bus will deteriorate, when ω is overly lowered. Therefore, ω should be carefully selected to better the bus inertia, yet not to severely impair DC bus stability margin.

B. Inductance and Capacitance Design in Boost Converter

The designs of inductance and capacitance mainly depend on the nominal system voltage and switching frequency of power switches [26]. Moreover, given the requirements of voltage ripple rate, current ripple rate, and continuous operating mode,

TABLE I
SYSTEM PARAMETERS

Parameter	Description	Value
$L_{SCj}, j = 1$	SC converter inductance	2 mH
$L_{Bj}, j = 1, 2, 3$	Battery converter inductance	2 mH
$C_{SCj}, j = 1$	SC converter capacitance	470 μ F
$C_{Bj}, j = 1, 2, 3$	Battery converter capacitance	470 μ F
V_{th}	Nominal bus voltage	170 V
r_1, r_2, r_3	Line impedance	2 Ω
$\bar{C}_{Bj}, j = 1, 2, 3$	Battery capacity	50 Ah
$R_j, j = 1$	Virtual resistance in (2)	2 Ω
ω	Crossover frequency of LPF	50 rad/s
P_v	Control matrix in (15a)	0.01
γ_v	Voltage control gain	0.01
P_E	Control matrix in (15b)	$\begin{bmatrix} 167.1242 & 5.0252 \\ 5.0252 & 0.3326 \end{bmatrix}$
M	Control matrix in (15b)	$diag([0.02 \ 1])$
$\mu_{v1}, \mu_{v4}, \mu_{jE1}, \mu_{jE4}$	Adaptive law parameters	1
$\mu_{v2}, \mu_{v3}, \mu_{v5}, \mu_{v6}$	Adaptive law parameters	250
$\mu_{jE2}, \mu_{jE3}, \mu_{jE5}, \mu_{jE6}$	Adaptive law parameters	250

it is possible to compute the minimum values for inductance and capacitance. Then the system designer would pick off-the-shelf products and integrate the power components to DC/DC converters.

C. Comparisons with Existing Methods

For addressing the attacks investigated in this paper, there are two types of approaches: observer-based control and vanilla adaptive control. In [27], nonlinear disturbance observer (NDO) can be designed to estimate the unknown time-varying superposition. However, the accuracy estimation of NDO necessitates that the observed quantity is a constant and it does not consider the impacts of the effectiveness-losing factor. Hence, the NDO based approaches would not fully resist the undesirable cyber attacks. The vanilla adaptive control reported in [28] is the simplified version of the proposed controller, which keeps only the linear terms in 15. The vanilla adaptive control, lacking nonlinear components, would be hard to achieve the expected control performance as in this paper.

D. Impacts of RES Severe Drop on Control Performance

Fig. 6 shows the simulation results of a case where a sudden PV power decrease happens. The cyber attacks are launched the same as in Fig. 8(d). Initially, the load power is set as 1252.3W, and this load is partially compensated by PV power. To better show the simulation process, the initial battery SOC's are identically set. At the instant of 30s, PV power suddenly drops to zero. The entire HESS is forced to output more power to handle the loading demand. The supercapacitor first bursts high current to overcome the loss of PV, and its current gradually reduces to zero in steady state. For the whole system transition, three batteries slowly increase their output currents to maintain the DC bus at a nominal value 170V. In this way, the dynamic power sharing between batteries and the supercapacitor, DC bus voltage regulation, and proportional power sharing among batteries have been perfectly realized.

E. Different Controls for Battery- and Supercapacitor- Interfaced Converters.

Fig. 6. Simulation results where a sudden PV power decrease happens.

Fig. 7. A controller hardware-in-the-loop (HIL) Opal-RT platform.

In the investigated HESS, the DC bus voltage is mainly regulated by the supercapacitor which, according to [26], the double PI control loop can be used. The outer loop is to drive the converter terminal voltage to track the reference. The inner loop help to force the inductor current to track the current reference given by the outer loop. In contrast, batteries are scheduled in current control mode. Hence, only inner current control loop is reserved.

VI. RESILIENCE CONTROL PRACTICE

In this section, controller hardware-in-the-loop (HIL) experimental platform and comprehensive studies are detailed, which helps to practice and verify the proposed resilience controller.

A. Experimental setup

Fig. 8. Sequential testing process. (a) Phase I: Initial SOC balancing; (b) Phase II: Attack #1 launched against u_v and u_{1E} ; (c) Phase III: Attack #2 launched against u_{2E} ; (d) Phase IV: Attack #3 launched against u_{3E} ;

Fig. 9. SOC balancing among three batteries in Phase I.

As shown in Fig. VI, the HIL platform consists of an Opal-RT 5600 simulator, three DSP28335 controllers, a host PC and an 8-channel oscilloscope. The electrical energy storage system depicted in Figs. 4-5 is realized in the Opal-RT 5600 simulator. It should be noted that the controller given in Fig. 4(c) for the SC is also established in the simulator, whereas the PI control in Fig. 4(d) for batteries and the proposed resilience controller are implemented in DSP controllers. Opal-RT simulator accepts the PWM signals generated from DSP controllers. PWM signals are further used to control the DC/DC converters of batteries. DSP control boards are with built-in Controller Area Network (CAN) communication interfaces. These interfaces would be used for data exchange between DSP boards and BeagleBone boards. BeagleBone can be programmed to create friendly user interface. The whole experimental setup forms up the complete cyber-physical hybrid energy storage system.

B. Resilience controller verifications

To corroborate the effectiveness of the proposed distributed resilience controller for CPHS exposed to unexpected attacks, the testing process imposed with sequential attacks is designed in Fig. 8.

1) *Phase I*: This phase allows for the initialization of CPHS where, by means of the resilience controllers in Fig. 4(a)-(b), SOC balancing among three batteries is performed in the case of no attacks. In this phase, P_L in Fig. 5 refers to a 300- Ω resistive load. The relevant experimental results are displayed in Fig. 9. The initial SOC of three batteries are 0.92, 0.90, and 0.88, respectively. To compensate for the system load, batteries should output some powers, and due to the regulation of resilience controller, SOC are continuously decreasing and eventually equalized after 4000 s (slightly above 1 hour). As mentioned previously, γ_E in (15) would help to adjust the dynamics of SOC balancing, i.e., smaller γ_E gives slower

Fig. 10. Experimental results of Phase II.

Fig. 11. Experimental results of Phase III.

convergence of SOC. In this paper, γ_E is chosen to be relatively small of 0.02 so as to avoid the large circulating current discharged from one battery to charge another. However, if a faster balancing process is expected, γ_E can be properly enlarged to flexibly accommodate practical needs.

2) *Phase II*: Note that the resilient voltage restoration control in Fig. 4(a) is realized in the DSP controller for battery #1, as it is assumed that only battery #1 can receive the reference signal (see Fig. 5). Following Phase I, attack #1, defined as $\phi_v = \phi_{1E} = 0.5$ and $\delta_v = \delta_{1E} = 50 \sin(100\pi t)$, is launched against battery #1. In this situation, experimental results showing system dynamics when a first 50- Ω load is connected to DC bus, is visible in Fig. 10. Before load changes, all the battery currents are 0.32 A. The current readings increase to 2.25 A after the load step-up, supplying more power to maintain the bus voltage. The proportional current sharing is in full agreement with the prior battery capacity settings (see (31)) where $I_{B1} : I_{B2} : I_{B3} = 1 : 1 : 1$. In transient state, the current of SC bursts to around 6.5 A and gradually reduces to zero, and batteries slowly output powers, which means transient current sharing between SC and batteries has been achieved. V_b is restored to 170 V although a voltage drop is observed when the load step-up is triggered.

3) *Phase III*: Upon the operation point in Phase II, in Phase III, attack #2 similar to attack #1 is imposed to battery #2, where $\phi_{2E} = 0.5$ and $\delta_{2E} = 50 \sin(100\pi t)$. System dynamics of the case when a second 50- Ω load is coupled to the DC bus are shown in Fig. 11. Battery currents smoothly climb to 4.17 A compensating for the low frequency components of load increase, whereas SC can handle the high frequency components. The overall transient process takes around 20 s, and the DC bus voltage is well stabilized at 170 V in steady state.

4) *Phase IV*: Proceeding to Phase IV in Fig. (12), attack #3 is further inflicted on battery #3 ($\phi_{3E} = 0.5$ and $\delta_{3E} = 50 \sin(100\pi t)$). Different from previous scenarios, in Phase IV,

Fig. 12. Experimental results of Phase IV.

Fig. 13. Comparative experimental results of the CPHS with conventional distributed controller and the proposed resilience controller.

the second resistive load is disconnected from the DC bus. From Fig. 12, when the load decrease happens, SC quickly absorb a certain amount of current, and battery currents slowly decline to 2.25 A. Holistically, it is obvious that proportional current sharing among batteries, transient current allocation between batteries and SC, and DC bus voltage restoration are all perfectly realized. By using the proposed resilience controller, cyber attacks exert negligible impact on the normal operations of the CPHS.

C. Comparative experimentation

Fig. 13 shows the comparative experimental results of the CPHS with conventional controllers and the proposed resilient controller under attacks. Loading condition is the same as in Phase I where only a 300-Ω resistive load is used. Then as understood from [29], the conventional controllers for voltage restoration, proportional current sharing, and SOC balancing can be derived as

$$u_v = -k_v B_v^T P_v \varepsilon_v, \quad (38a)$$

$$u_{jE} = -k_{jE} B_E^T M P_E \varepsilon_{jE}. \quad (38b)$$

For fair comparisons, all parameters in (38) are set the same as in (15) except that k_v and k_{jE} are configured as the steady state values of $\hat{b}_v$ and $\hat{b}_{jE}$, respectively, i.e., $k_v = k_{jE} = 110$. It is seen from Fig. 13 that, at the beginning, all three attacks in Fig. 8 are executed simultaneously, and serious oscillations happen to currents and the bus voltage. This would not be accepted in real-life system operation, as oscillations may cause damage to electrical devices or even collapse the whole system. Once the proposed resilience controller is enabled, the undesirable oscillations are effectively suppressed to almost zero, which significantly enhances the resilience of the CPHS.

VII. CONCLUSION

This paper proposes a novel resilience control for cyber-physical hybrid energy storage systems (CPHSs). The resilience

control with adaptive laws can suppress the impacts of cyber attacks on normal system operations and ensure the realizations of DC bus voltage recovery, transient current allocation between batteries and SCs, proportional battery current sharing, and battery SOC balancing. In addition, the proposed control only needs communication among batteries and SCs would not involve data exchanging process, which definitely saves the system capital costs. Detailed parameter configurations are provided to attain desired system performances. The effectiveness of the proposed resilience control is verified on a HIL testing platform. The results show that the control method outperforms the conventional distributed controller and largely improves the system resilience against cyber attacks.

VIII. APPENDIX

Lemma [24] Assuming the undirected graph is connected, all the eigenvalues of matrix $(L + G) > 0$ satisfy $\lambda_m \geq \dots \lambda_3 \geq \lambda_2 \geq \lambda_1 > 0$.

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