State Feedback Control-Based Optimal Management of a Modular Second-Life Battery for Grid Energy Storage

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Introduction

Battery modules retired from electric vehicles typically retain more than two thirds of their initial capacity and could typically deliver additional 5-8 years of service in a secondary application. Academic studies [1] estimate a range of 112-275 GWh per year of second-life batteries (SLBs) becoming available by 2030 globally. However, in a modular SLB system, different SLB modules could have different nominal maximum and minimum open circuit voltage, degraded initial capacity, lumped internal impedance, initial state of charge (SoC), state of health (SoH), and degradation rate. It is necessary to apply a control strategy that can handle the state difference among and adapt with the degradation of the SLB modules to achieve the optimal energy efficiency of the modular SLB system.

Modular SLB System

A single-phase modular SLB system consisting of SLB modules and a MPC for grid energy storage is studied. The MPC consists of a cascaded H-bridge converter and an H-bridge unfolder. The left leg of each H-bridge of the cascaded H-bridge converter is connected to an SLB module and works as a non-isolated bidirectional dc-dc converter to regulate the DC-link voltage of the H-bridge to be constant. All the right legs of the H-bridges of the cascaded H-bridge converter form a cascaded half-bridge converter which outputs a nonnegative stair-case voltage, where the number of stairs is equal to the number of SLB modules. The H-bridge unfolder is used to convert the nonnegative stair-case voltage input to an AC voltage output by changing the polarity of the stair-case voltage input each half cycle.

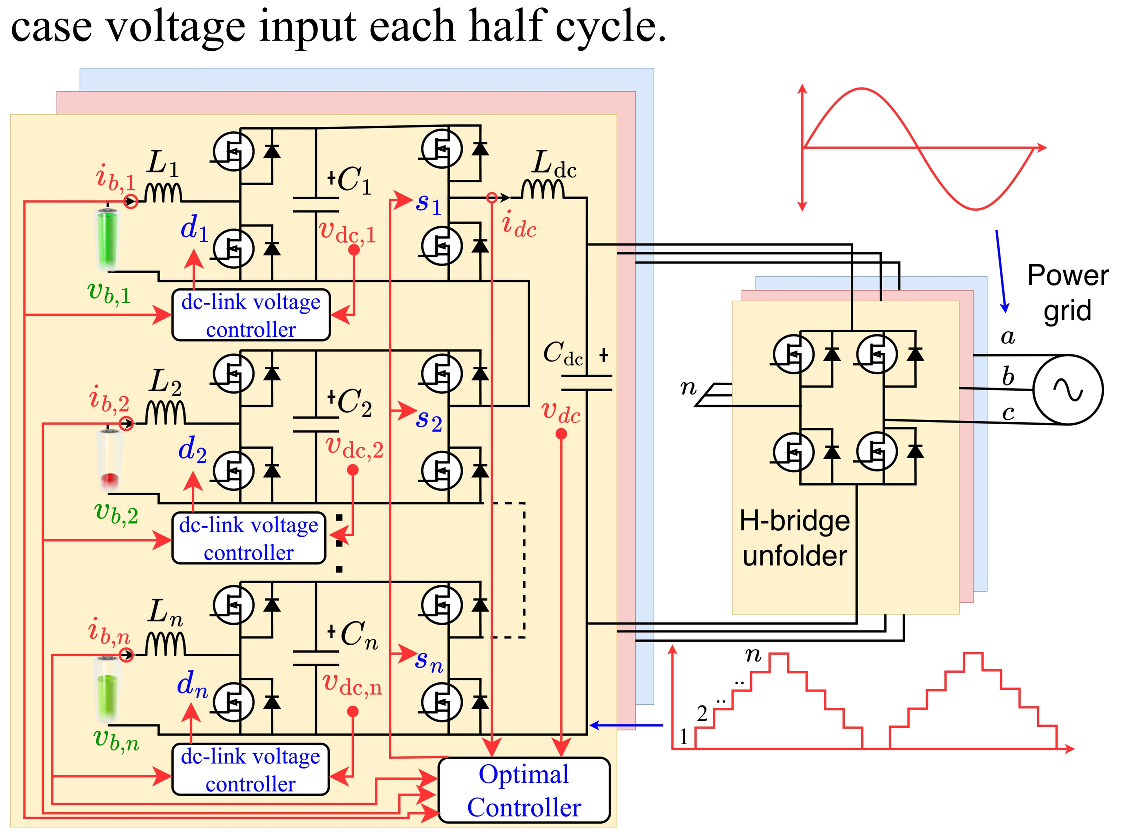

Fig. 1. A modular SLB system for grid energy storage.

Optimal Controller

The relationship between the SoC and the current of each SLB module is represented as

$$\Delta_{t-\Delta t}^{t} SoC_i = \frac{\int_{t-\Delta t}^{t} i_{b,i}\, dt}{3600 \times Q_i \times SoH_i}.$$

Since the SoH of the SLB module degrades faster as the module is discharged with a larger current, the objective of the optimal controller is to manage power sharing among the SLB modules by minimizing the output current of each SLB module while maintaining a desired root mean square (rms) value of the staircase voltage output of the cascaded H-bridges.

The optimal controller is designed based on the linear quadratic integral (LQI) control technique.

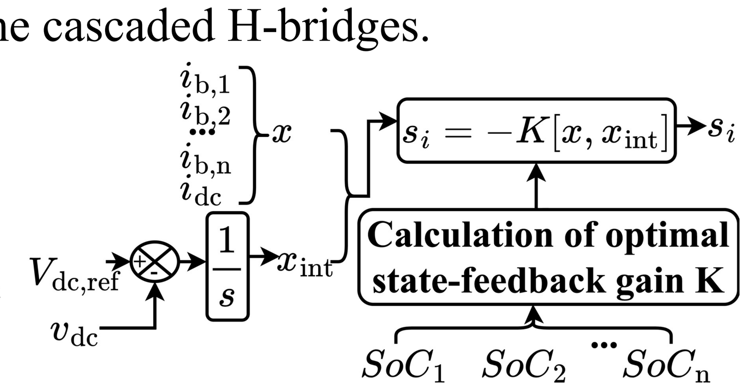

Fig. 2. Optimal LQI controller.

For a finite-horizon optimal problem, the cost function can be expressed as

$$J = \int_{t_0}^{t_f} ([x, x_{\text{int}}]^T Q [x, x_{\text{int}}] + u^T R u) dt$$

where x represents the state vector; x_{int} is the additional state to achieve a fixed rms value of the staircase voltage (v_{dc}); Q and R are the diagonal weight matrices to penalize the deviations on the states being optimized and the inputs, respectively. One of the methods to solve this quadratic optimization problem is Algebric Ricatti Equation (ARE) from which the optimal control input (u^*) to the system is obtained using

$$u^* = -(R + B^T PB)^{-1} B^T PAx = -Kx = v_{b,i}^*$$
$$P = A^T PA - (A^T PB)(R + B^T PB)^{-1}(B^T PA) + Q$$

The optimal duty ratios (s_i^*) are generated using $s_i^* = \frac{v_{b,i}^*}{v_{b,i,max}}$. As $v_{b,i}^* \leq v_{b,i,max}$ due to the input constraint, $s_i^* \leq 1$.

$$\begin{bmatrix} \dot{i}_{b,1} \\ \dot{v}_{dc,1} \\ \dot{i}_{b,2} \\ \dot{v}_{dc,2} \\ \cdots \\ \dot{i}_{b,n} \\ \dot{v}_{dc,n} \\ \dot{i}_{dc} \\ \dot{v}_{dc} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1-d_1}{L_1} & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ \frac{1-d_1}{C_1} & -\frac{S_1}{R_{dc}C_1} & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1-d_2}{L_2} & \cdots & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1-d_2}{C_2} & -\frac{S_2}{R_{dc}C_2} & \cdots & 0 & 0 & 0 & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1-d_n}{L_n} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1-d_n}{C_n} & -\frac{S_n}{R_{dc}C_n} & 0 & 0 \\ 0 & \frac{S_1}{L_{dc}} & 0 & \frac{S_2}{L_{dc}} & 0 & 0 & \frac{S_n}{L_{dc}} & 0 & -\frac{1}{L_{dc}} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{C_{dc}} & -\frac{1}{R_{dc}C_{dc}} \end{bmatrix} \begin{bmatrix} i_{b,1} \\ v_{dc,1} \\ i_{b,2} \\ v_{dc,2} \\ \cdots \\ i_{b,n} \\ v_{dc,n} \\ i_{dc} \\ v_{dc} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} & 0 & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & 0 \\ 0 & \frac{1}{L_2} & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & 0 \\ \cdots & \cdots & \cdots & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{L_n} \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v_{b,1} \\ v_{b,2} \\ \cdots \\ v_{b,n} \end{bmatrix}$$

Result

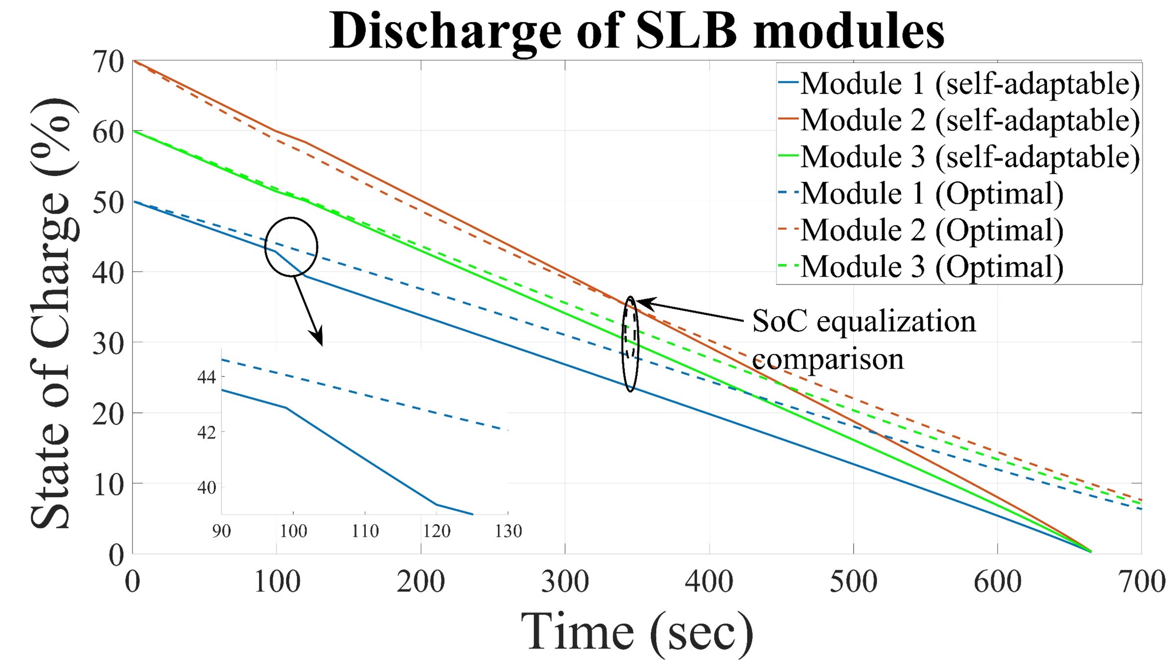

Fig. 3. SoC trajectories of the SLB modules with the proposed controller and self-adaptation controller during discharge.

A three-module SLB system (i.e., n = 3) is modeled in MATLAB/Simulink for the validation of the proposed control strategy. Table. I lists the parameters of the SLB system. Different SLB modules have different degraded initial capacity, nominal minimum and maximum open circuit voltage, and used cycles. Fig. 3 compares the SoC trajectories of the three SLB modules when the system is discharged to supply a resistive load using the self-adaptation control strategy [3] and the proposed optimal control strategy. The dynamic capacity fading of the SLB modules is a phenomenon when several parallel connected cells of an SLB module suddenly fail. This is simulated by doubling the internal impedance of a single SLB module while the system is in operation [4], [5]. A smoother transient behavior is observed in the case of using the proposed optimal control strategy; the SLB modules tested with the proposed optimal control strategy have higher SoCs, i.e., more charges left than the SLB modules tested with the self-adaptation control, which are completely discharged at the end of the process. The result indicates that the proposed control strategy improved the energy efficiency of the system.

Moreover, the SoC equalization is also faster in the case of using the proposed control strategy compared to the state-of-the-art control strategy.

Conclusions

This work proposed an optimal linear feedback control strategy based on the LQI method for the energy management of a modular SLB system for grid energy storage applications. The proposed control strategy is capable of handling transients such as SLB voltage drop, sudden change in load, and fault in any SLB module, etc. while achieving the maximum energy efficiency of the SLB system. An estimation of battery degradation is not required in the proposed controller.

Table. I: SLB System Parameters

Parameter	Values
SLB module parameters	
Maximum nominal voltage ($v_{\text{dc},i,max}$)	24V
Nominal capacity of the three modules	10Ah, 12.5Ah, 11.5Ah
SoC of the three modules (SoC_1, SoC_2, SoC_3)	70%, 60%, 50%
Boost converter parameters	
Inductance (L_i)	200 µH
Capacitance (C_i)	447 µF
Reference dc-dc converter output voltage (V_{ref})	48V
Switching frequency	10kHz
Duty ratio for optimal controller design (d_i)	0.5
DC-link parameters	
DC-link inductance (L_{dc})	200µH
DC-link capacitance (C_{dc})	447µF
DC-link reference rms voltage ($V_{\text{dc},ref}$)	100V
Duty ratio of the right leg of each H-bridge (s_i)	1
Power grid parameters	
Constant resistive load (R_{dc})	3Ω

References

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