Optimal Management of Modular Second-Life Batteries with Reference Tracking for Three-Phase Grid Energy Storage

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Introduction

Retired electric vehicle battery modules retain over two thirds of their initial capacity, offering 5-8 years of additional service in secondary applications. By 2030, forecasts suggest a global availability of 112-275 GWh per year of second-life batteries, potentially providing low-cost energy storage for accommodating renewable energy on the power grid [1]. Due to the advantages in medium and high voltage applications, modular multilevel converter (MMC) structure is commonly adopted for battery energy storage systems (BESS). A double loop linear quadratic regulator (LQR)-based optimal power sharing control method with optimal reference tracking (ORT) of a cascaded H-bridge converter integrated modular second-life battery (SLB) system for grid energy storage application is presented. The outer loop of the proposed LQR control strategy reduces the quadratic value of the power error, while the inner loop adjusts the corresponding power sharing according to the SLB parameter changes, e.g., capacity degradation, faulty SLB module, state-of-charge (SOC), etc.

Modular SLB System

A three-phase modular SLB system consisting SLB modules and a double loop LQR based optimal controller is presented. The left leg of each H-bridge converter is connected to an SLB module using a non-isolated bidirectional dc-dc converter to regulate the module DC-link voltage to be constant. All the right legs of the H-bridge converter form a cascaded H-bridge which outputs a nonnegative stair-case voltage, where the number of stairs equals to the number of SLB modules. The H-bridge unfolder in each phase converts the nonnegative stair-case voltage input to an AC voltage output by changing the polarity of the stair-case voltage each half cycle.

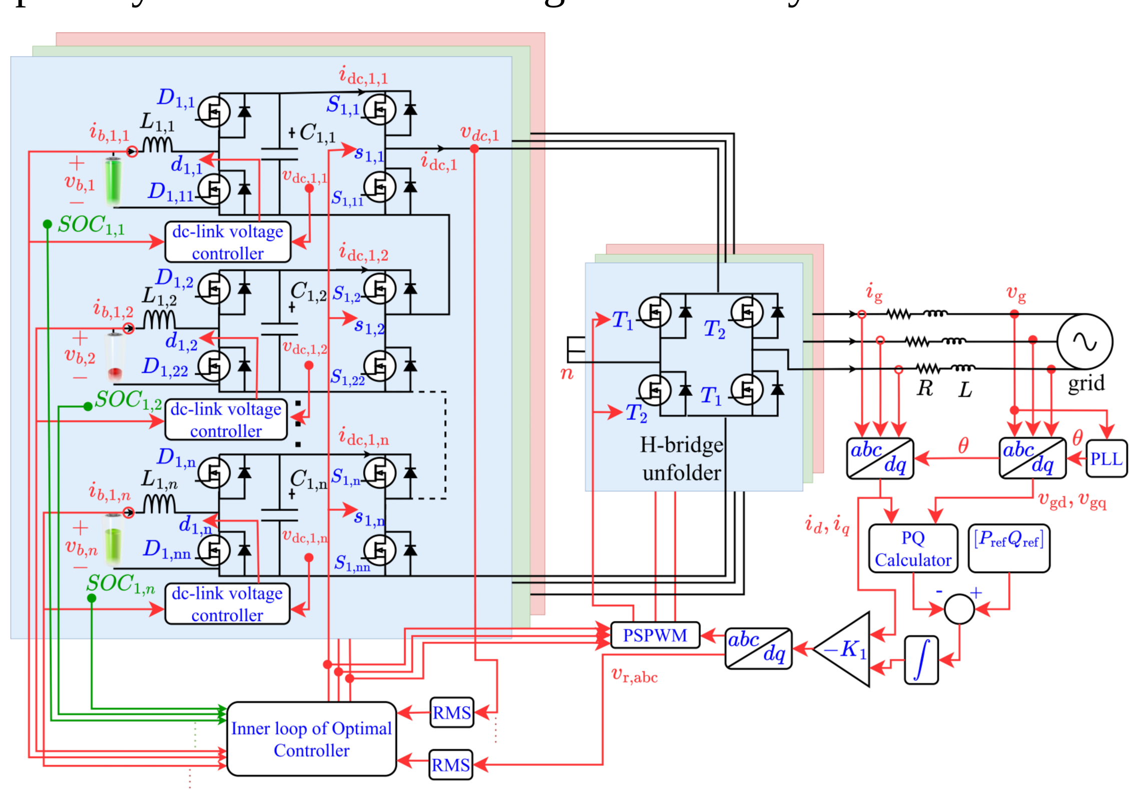

Fig. 1. A modular SLB system for grid energy storage..

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

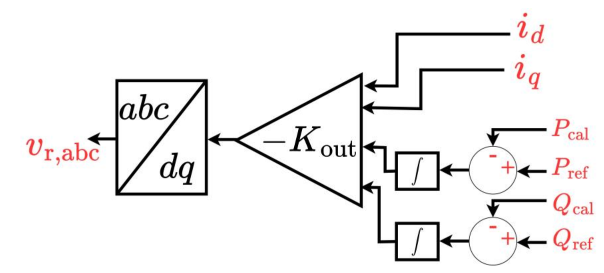

Fig. 2. Outer loop of the proposed optimal LQI controller..

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

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 Algebraic Ricatti Equation (ARE) from which the optimal control input (u^*) to the system is obtained using

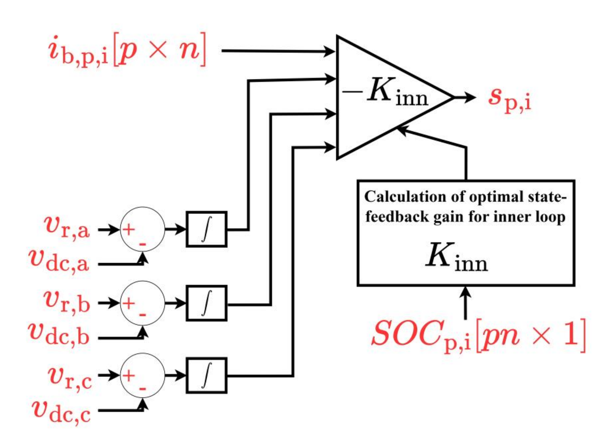

Fig. 3. Inner loop of the proposed optimal LQI controller.

$$u^* = -(R + B^T P B)^{-1} B^T P A x = -K x = v_{b,p,i}^*$$
$$P = A^T P A - (A^T P B)(R + B^T P B)^{-1}(B^T P A) + Q$$

The outer loop of the controller optimally tracks the reference active and reactive power, and the inner loop manages the power sharing among the SLB modules.

$$Q_{\text{inn}} = \begin{bmatrix} Q_{\text{SLB }1,1} & 0 & 0 & 0 & \ldots & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \ldots & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & Q_{\text{SLB }1,2} & 0 & \ldots & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \ldots & 0 & 0 & 0 & 0 & 0 \\ \ldots & \ldots & \ldots & \ldots & \ldots & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & Q_{\text{SLB }3,n-1} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & Q_{\text{SLB }3,n} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 100 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 100 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 100 \end{bmatrix}$$

For SOC equalization, the penalty for the SLB module with highest SOC will be the highest for charging and the lowest for discharging. Thus, $Q_{SLB,p,i} = \frac{SOC_{p,i}}{100 - SOC_{p,i}}$ is used for the charging process, $Q_{SLB,p,i} = \frac{100 - SOC_{p,i}}{SOC_{p,i}}$ for the discharging process and, weightage for the integral states are constant throughout the experiment which decides the fastness in transient response of the inner loop.

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

Result

The performance of the proposed double loop optimal control strategy is evaluated using MATLAB simulation studies on a three-phase grid connected SLB system with four SLB modules (i.e. n=4) in each phase with different initial SOCs, and capacities. The parameters of the simulated system are provided in Table I. The objective of the outer loop of the proposed controller is validated with the reference power tracking response shown in fig.4. Whereas the objective of the inner loop of the proposed controller is SOC equalization among the SLBs in each phase considering the SOH of the SLB modules, is validated with a charging (P_{ref}=-500, Q_{ref}=0) and discharging (P_{ref}=500, Q_{ref}=0) pulse of 1000 seconds, and 50% duty cycle representing in fig.5.

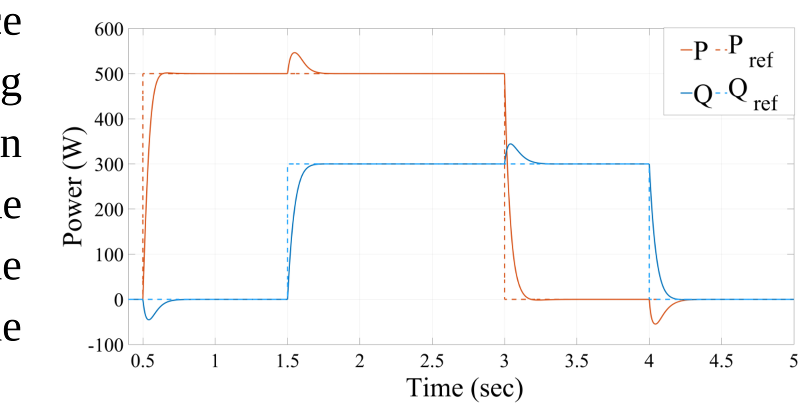

Fig. 4. Optimal reference power tracking

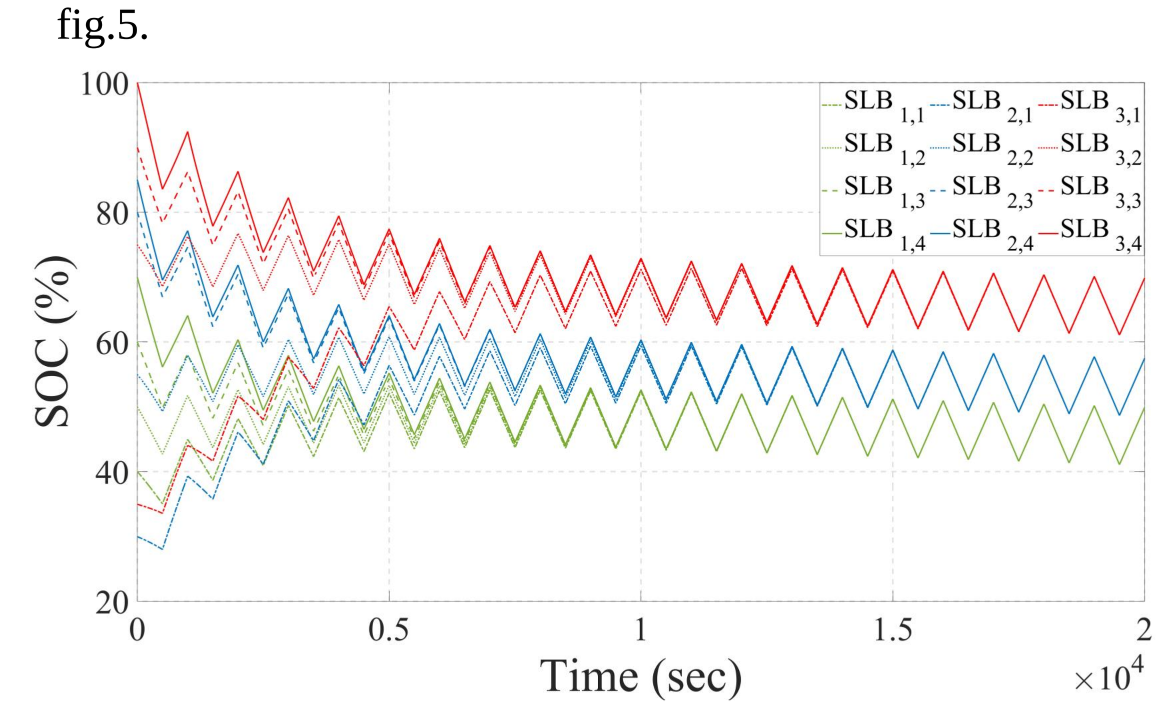

Fig. 5. SOC equalization of the SLB modules in each phase.

Conclusions

This work proposed an optimal double loop linear state-feedback control strategy based on the LQI method for the energy management of a three-phase grid connected modular SLB system. The proposed control strategy is capable of optimal power reference tracking, and SOC equalization of SLB modules in each phase, without estimation of the battery degradation. Thus, the proposed controller is computationally efficient for the grid energy storage application.

Table. I: SLB System Parameters

Parameter	Values
SLB module parameters	
Maximum nominal voltage ($v_{\text{dc},i,max}$)	24V
Nominal capacity of the 12 modules ($Q_{11}, Q_{12}, Q_{13}, Q_{14}, Q_{21}, Q_{22}, Q_{23}, Q_{24}, Q_{31}, Q_{32}, Q_{33}, Q_{34}$)	11Ah, 10Ah, 12.5Ah, 11.5Ah, 9Ah, 10Ah, 12Ah, 14Ah, 11.5Ah, 12Ah, 13.5Ah, 11Ah
SoC of the 12 modules ($SOC_{11}, SOC_{12}, SOC_{13}, SOC_{14}, SOC_{21}, SOC_{22}, SOC_{23}, SOC_{24}, SOC_{31}, SOC_{32}, SOC_{33}, SOC_{34}$)	35%, 75%, 90%, 100%, 30%, 55%, 80%, 85%, 40%, 50%, 60%, 70%
Boost converter parameters	
Inductance ($L_{\text{p,i}}$)	200 μH
Capacitance ($C_{\text{p,i}}$)	447 μF
Reference dc-dc converter output voltage ($V_{\text{ref,pi}}$)	48V
Switching frequency	10kHz
Duty ratio for optimal controller design ($d_{\text{p,i}}$)	0.5
Grid side parameters	
Filter inductance (L)	44μH
Filter resistance (R)	10Ω

References

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