

# Current Sharing Control for Cascaded H-Bridge Applied to Secondary Use Batteries in Community Energy Storage Systems

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**Abstract** – This paper presents a cascaded H-bridge inverter topology for the application of secondary-use batteries as grid-connected energy storage. The proposed control strategy allows a degree of control over individual battery currents while the total system follows an arbitrary current command. This enables the aggregation and optimal use of battery packs with different capacities and states of health, overcoming a significant drawback of existing implementations.

## I. INTRODUCTION

The ever-increasing demand for energy and the resulting strain on electric power infrastructure has created a market for novel, cost-effective energy management technology. Building new power stations and transmission lines is one way to meet the demand, but these are very expensive solutions, and must be designed for peak demand. Introducing storage into the network can allow more efficient use of existing transmission and generation equipment. Widespread adoption would allow power plants to run at peak efficiency while storage charges or discharges to meet the load requirement. Transmission lines would need only to carry the average power, rather than being capable of carrying the peak power and going under-utilized at other times. The result is better return on investment for the generation, transmission, and distribution operators, as well as a business opportunity for the storage operator [1].

Chemical batteries are a promising option for grid-connected storage – they offer high energy density, scalability, and a stiff voltage (as compared to PV cells or supercapacitors, for example). However, batteries suffer from several drawbacks: the initial cost is high, round-trip efficiency may be poor, capacity degrades with time and cycling, and they are sensitive to temperature.

The increasing prevalence of electric vehicles offers an interesting opportunity for overcoming one of the most significant barriers—cost. The traction application is an extremely demanding one, and batteries which have spent their useful life in that application may still be suitable for a less demanding one. Reference [2] defines end-of-life for traction batteries to be the point at which the capacity has fallen to 80% of nominal. At this point, the ability of the batteries to supply large bursts of current is substantially degraded, but they are still typically suitable for bulk energy storage at low current levels. Rather than recycling these batteries, the remaining capacity can be put to use as grid-connected energy storage, providing both economic and environmental benefits.

Multilevel converters have been considered in the past

for high power, high-voltage applications where the available power electronics device limitations do not allow for single-stage topologies to be utilized. In [3, 4] authors apply the cascade H-bridge topology to three-phase energy storage systems. The papers present an approach where the neutral current is used to provide unequal currents from each of the batteries. In [5, 6] authors present a method to achieve voltage balancing for a single phase cascaded bridge. The control approach relies on the slower voltage loop to balance the currents, while the fast current loop ensures that the load is supplied. This approach is not conducive to be applied to battery energy storage systems, since the voltage of the battery does not change dramatically with load or state of charge (unlike the PV cells or supercapacitors in [5, 6]).

This paper proposes a control strategy that uses a proportional-resonant controller to satisfy the commanded current. The controller generates a “master” duty cycle for the inverter, which may then be scaled independently for each bridge. The proposed control method allows for unequal currents to be supplied by each battery, in accordance with the battery capacity and state of charge. The proposed approach enables optimal utilization of the available capacity of the battery.

## II. CASCADED INVERTER TOPOLOGY

The system presented is a single phase, four-stage cascade H-bridge inverter which interfaces the batteries directly with the grid—there is no intermediate DC link. This topology was chosen for modularity, to minimize stress on individual components, and to allow use of polyphase PWM techniques. A detailed comparison of the two topologies is beyond the scope of this work.

The experimental system interfaces with the utility at the lowest distribution level: 120V. It is fed from four 26V Lithium battery modules and is designed for a maximum power output of 2kW. In order to prevent uncontrolled rectification, the total available DC voltage must remain greater than the peak AC voltage at all times, so a transformer will be required to interface with the grid. A 3 kVA transformer with 2.5:1 turns ratio (48V output with center tap) was chosen for this purpose. Fig. 1 gives a top-level schematic for the system. The voltage source  $V_g$  represents the grid voltage via transformer.

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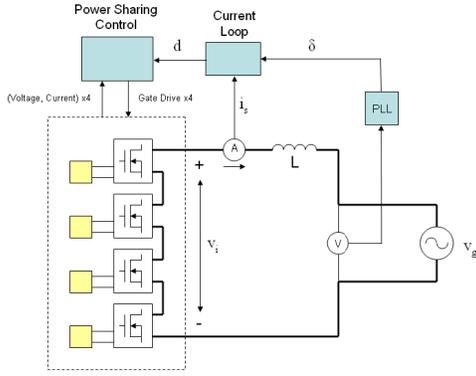


Fig. 1. Control Overview

### III. CONTROL DESIGN

The nature of the single-phase connection precludes the use of true rotating-frame control. However, a proportional-resonant (PR) scheme as described in [7] provides single-phase, stationary frame control which is equivalent to a PI in the rotating frame. One or more resonant elements may be employed to drive steady state error to zero at multiple frequencies; however, only one at the fundamental (60Hz) is used in this work.

A block diagram of the controller is given in Fig. 2. Using the commanded d- and q-axis current magnitudes and the measured grid phase, an AC command current is calculated. The error between this and the measured inductor current is passed to the PR controller for compensation. Figs. 4 and 5 give example responses to current command steps.

Using estimates of the grid voltage magnitude and coupling inductor size, it is possible to predict the inverter voltage that will drive the commanded current. Dividing by the total DC voltage, this voltage represents the “feedforward duty” that can optionally be added to the PR controller output to improve response time.

The goal of this system is to supply or consume power as commanded by an external operator, rather than to perform any independent voltage or phase regulation. Due to the small size of individual systems, the grid voltage is assumed to be stiff; therefore a simple and robust current controller is adequate to perform the desired functions. The aggregate fleet may be called upon for regulation, but this control would be performed at a higher level.

Following Fig. 1 and assuming the system operates at

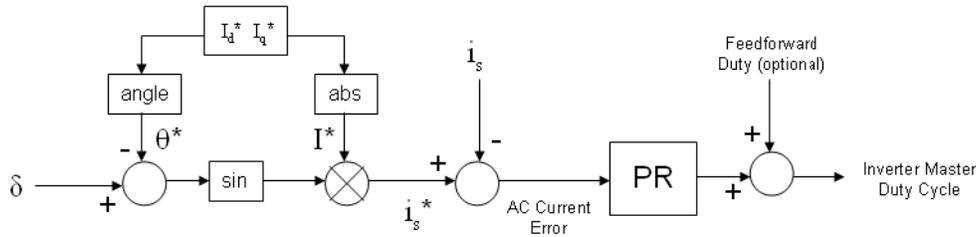


Fig. 2. Current Loop

a single frequency, the relationship between voltage and current is given by

$$\bar{i}_L = \frac{\bar{v}_i - \bar{v}_g}{j\omega L} \quad (1)$$

Where

$$\bar{v}_g = V_g e^{j\omega t} \quad (2)$$

$$\bar{v}_i = V_i e^{j\omega t + \phi} \quad (3)$$

$$\bar{i}_L = I_L e^{j\omega t - \theta} = I_d e^{j\omega t} + I_q e^{j\omega t - \pi/2} \quad (4)$$

This relationship can be represented graphically as in Fig. 3. The margin between total DC voltage and peak AC voltage seen by the inverter dictates the maximum real and reactive power than can be supplied.

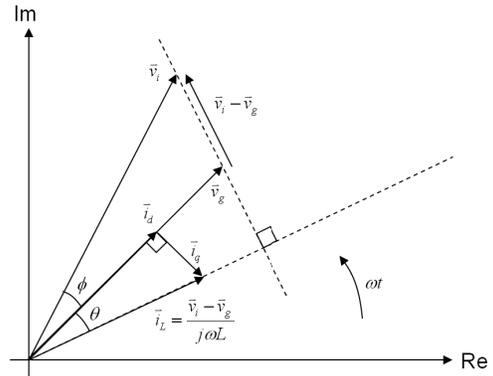


Fig. 3. Single Phase VSI Vector Diagram

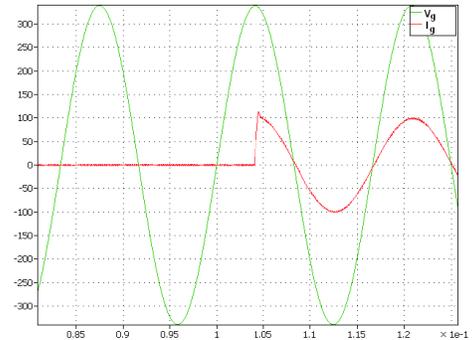
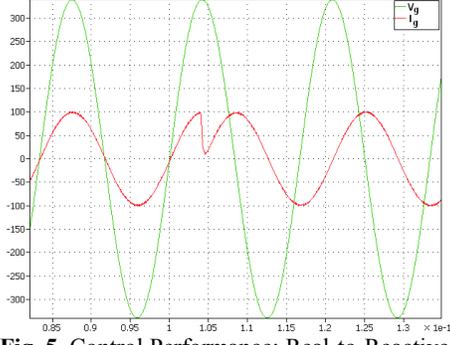


Fig. 4. Control Performance: Real Power Step ( $I_d^* = 100A$ )



**Fig. 5.** Control Performance: Real-to-Reactive Power Step ( $I_d^*$ ,  $I_q^* = 100A$ )

An inverter voltage in phase with the grid will drive purely reactive power according to

$$Q = \frac{V_g (V_i - V_g)}{\omega L} \quad (5)$$

An inverter voltage chosen such that  $\bar{v}_i - \bar{v}_g$  is orthogonal to the grid voltage will drive purely real power according to

$$P = \pm \frac{V_g \sqrt{V_i^2 - V_g^2}}{\omega L} \quad (6)$$

Averaged over each switching cycle, the inverter voltage can be expressed as a “master” duty cycle multiplied by the sum of the DC voltages,

$$v_i(t) = \text{Re}\{\bar{v}_i\} = d(t) \sum V_n \quad (7)$$

A set of gains  $k = [k_1 \ k_2 \ k_3 \ k_4]$  are introduced to scale the duty to each bridge such that

$$d_n(t) = k_n d(t) \quad (8)$$

In order not to disturb the total control loop gain,  $k$  must be normalized such that  $\text{mean}(k) = 1$ . The DC-side current of each bridge is given by

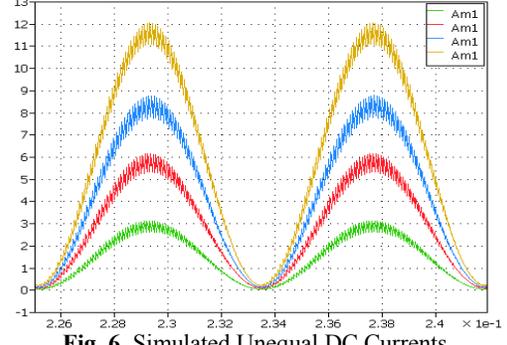
$$i_n(t) = d_n(t) i_L(t) \quad (9)$$

The output current  $i_L$  is assumed to be as commanded, a valid assumption provided that the controller is in steady state and at least one duty is not saturated. Rearranging Eqs. (1,7,8) and substituting in Eq. (9) yields

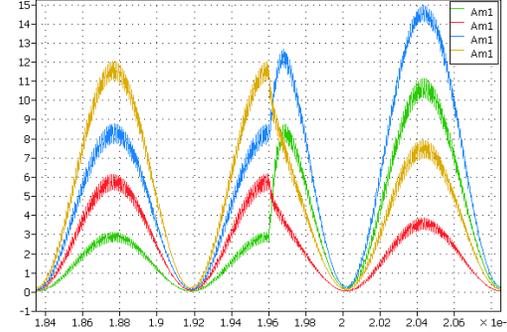
$$i_n(t) = \frac{k_n}{\sum V_n} i_L(t) \text{Re}\{j\omega L \bar{i}_L + \bar{v}_g\} \quad (10)$$

Thus the DC-side current scales linearly with relative gain, provided that the control does not drive one or more duty cycles outside the range  $[-1,1]$ . This is confirmed in simulation even for a substantial spread of DC source voltages. Fig. 6 shows simulated DC-side currents for gains  $[0.4 \ 0.8 \ 1.2 \ 1.6]$  applied to (ideal) sources of  $[20 \ 80 \ 30 \ 40]$  volts.

The gains may be either static or time-varying, depending on the goals of system-level control and the need to respond to changing battery and load conditions. Fig. 7 shows simulated battery currents as gains are reassigned from  $[0.4 \ 0.8 \ 1.2 \ 1.6]$  to  $[1.2 \ 0.4 \ 1.6 \ 0.8]$ .



**Fig. 6.** Simulated Unequal DC Currents



**Fig. 7.** Simulated DC Currents During Gain Reassignment

#### IV. EXPERIMENTAL RESULTS

Real-time control is implemented using Opal-RT RT-LAB software, MATLAB Simulink with Opal-RT blockset, and a specialized PC with analog and digital I/O hardware. The four H-bridges and related feedback sensor circuits were designed and constructed in-house.

During development, experiments were performed with a 24V grid connection, using half of the center-tapped transformer. We utilize 24V Li-ion battery packs provided for this project by the National Renewable Energy Lab in Golden CO. Grid-connected four-quadrant current control and unequal current sharing functions are proven using just two bridges; scaling to four or more bridges is simple. Fig. 8 shows this experimental system.

The oscilloscope captures in Figs. 9-12 demonstrate basic closed-loop functionality in grid-connected operation. The upper trace is grid voltage (via transformer); the lower one is inductor current. Command current magnitude was 5A in each case, and all four quadrants of the d-q plane were tested.



**Fig. 8.** System Configuration

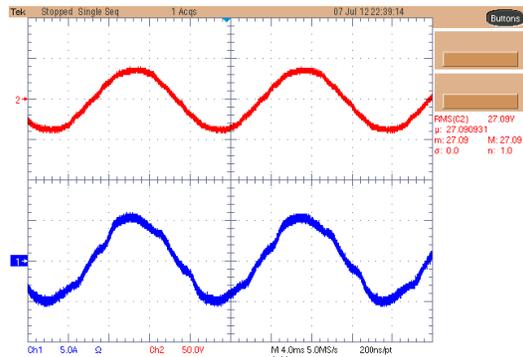


Fig. 9. Supplying Active Power to Grid

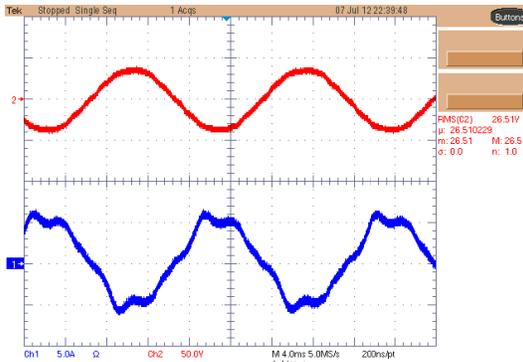


Fig. 10. Consuming Active Power from Grid

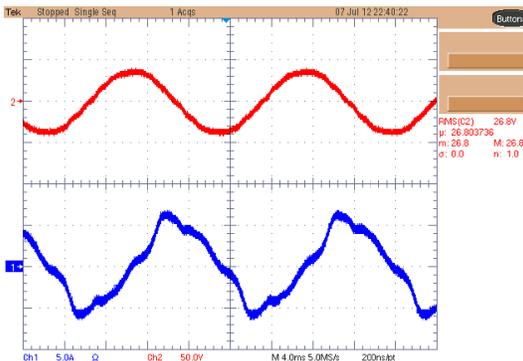


Fig. 11. Supplying Reactive Power to Grid

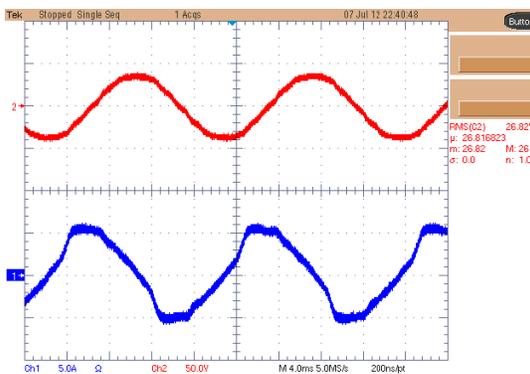


Fig. 12. Consuming Reactive Power from Grid

Fig. 13 shows unequal current sharing on the DC-side (lower two traces). These are displayed as voltages on the scope with a scale 1V/A (1A/div as shown). Duty gains were set to [0.8 1.2]. Fig. 14 shows unfiltered DC-side currents under the same conditions, zoomed to show difference in duty cycle. Note that the PWM phases are offset by  $\frac{1}{2}$  cycle at 10kHz to reduce current ripple.

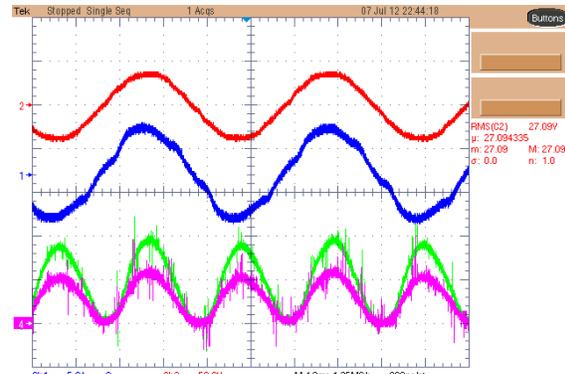


Fig. 13. Unequal Current Sharing (filtered)

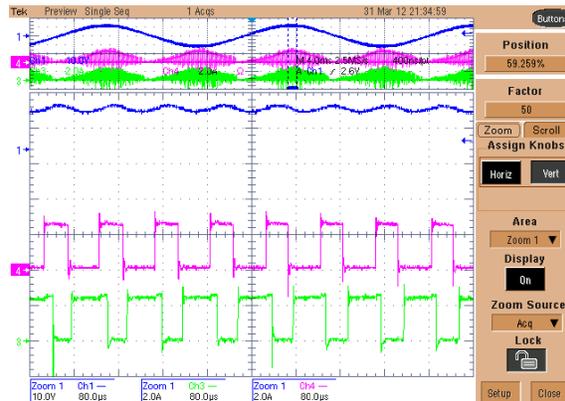


Fig. 14. Unequal Current Sharing (unfiltered)

Fig. 15 shows the hardware system response to a step command in d-axis current (5A). Response time is slower than in simulation due to conservative controller gains, as instability in hardware has the potential to destroy components. These will be carefully tuned for faster response in the future.

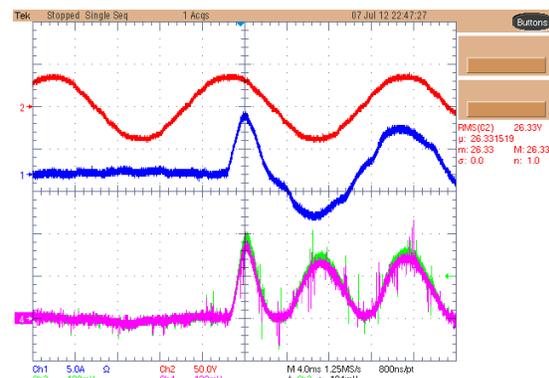


Fig. 15. Hardware Controller Step Response

## V. CONCLUSION

Community Energy Storage offers several potential benefits for electric utility operators, the electric vehicle market, and the environment. Storage of this type can provide economic opportunities as well as more reliable electric service. Using electric vehicle batteries in particular could lead to reduced EV cost, and deferral of recycling has environmental benefits.

Simulation results show that independent control of battery currents is possible without a high degree of controller complexity, and without disturbing overall system performance. This is a critical function that enables the combination of dissimilar batteries. The relative fraction of current supplied by each battery can be changed in real-time in response to changing conditions.

Experimental results at this time confirm all basic functions of the hardware system. Grid-connected four quadrant P-Q control has been demonstrated up to about 50VA, and independent control of DC source currents verified. Scaling to higher voltage and power levels is a simple matter of adding more H-bridges to the series.

## VI. ACKNOWLEDGEMENT

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