Combined Energies Whitepaper 1: Optimized SiC-based DC-DC conversion systems for energy storage and generation management.

Application: Flow batteries for data centers

Energy storage and DC-power sources generate voltage based on the ideal potential energies of their respective chemistries and are typically on the order of 1-4 volts per electrochemical cell. This voltage is independent of the size of the cell, which determines the amperage the cell is capable of producing, usually measured on an amps/cm^2 basis. These two parameters determine the power, in watts, produced by the cell. Equating voltage to water pressure, it is difficult to get low voltage power to do useful work, and these voltages are usually increased by running electrochemical cells in series, making their voltages additive. Since the inputs and outputs of the cells are electrically tied, the total system power is limited by the lowest or weakest cell. As repeat units are added, voltage and amperage are increased linearly, and as voltage increases, the amperage required to deliver an equivalent amount of power decreases. All energy storage and electrochemical generation applications have voltage limits based either on the chemistries involved or electrical insulation considerations.

Critical DC power system architectural choices include the size and number of cells. This dictates the operating voltage range and amperage the system can deliver. With the advent of electric vehicles, configurations consisting of large numbers of physically small cells, integrated in series, have been preferred to provide high voltage thereby reducing required amperage and making the inverters, motors, cables and connectors as small and light as possible. These configurations have almost exclusively relied on Lithium-ion batteries because of their high power density, comparatively light weight and ability to operate at elevated voltages. Due to their cost and limited life, however, small form factor, high cell count Lithium-ion is increasing being viewed as inappropriate for bulk energy storage or to be employed as an energy source.

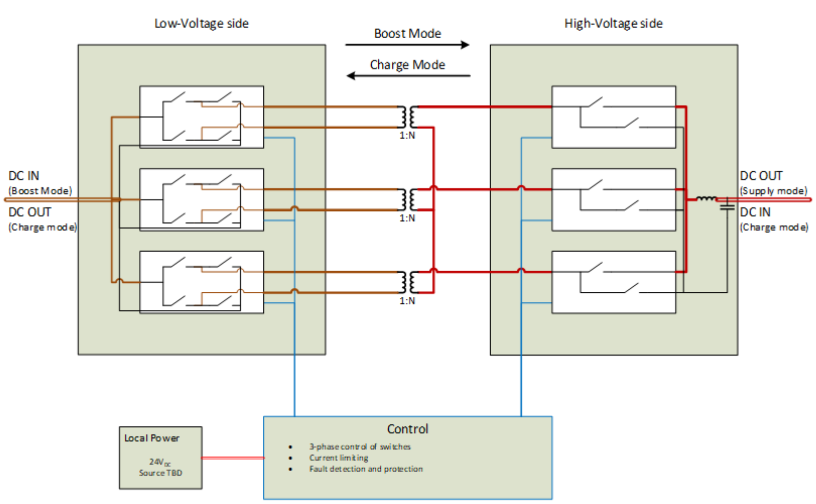
Typical bulk energy storage solutions using rechargeable lead acid, nickel-metal hydride or nickel iron chemistries have low voltage (12V, 24V and 48V) battery management systems and inverters for small, typically residential, applications. Larger solutions must employ longer battery strings to increase voltage and reduce the size of connecting cables, connectors and busbars. This decreases battery output, since all cells in a string must follow the lowest performing cell, risking thermal runaway from cells that become net consumers of power, and life since heathy batteries are overcharged in an attempt to fully charge all cells. These effects are significant enough for operators of critical energy storage applications to often replace their batteries after less than 12.5% of their rated use/charge cycles.[1] Energy storage also requires a separate charging circuit and battery management system. Additionally, bulk energy storage is sensitive to AC ripple from the grid and harmonics from motors and power equipment connected locally. These phenomena further contribute to internal heat generation, charge fluctuations and decreased performance and life.

[1] Cutler-Hammer application note: *Improving Life of Parallel Connected Battery Strings*

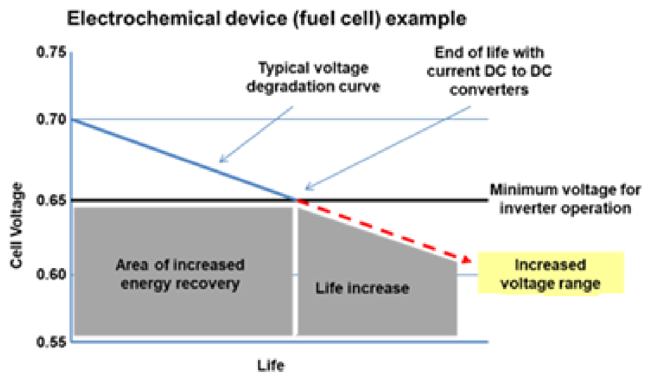
Electrolytic DC generation systems such as flow batteries and fuel cells have the same architecture considerations as energy storage with increased performance sensitivity and restrictions. Because of fluid reactants (fuel cells) and electrolyte (flow batteries) as well as thermal management requirements, these generators prefer a relatively fewer number of larger format cells and lower operating voltages. This presents challenges for commercially available power electronics, specifically: variable, low voltage power output, high current, large cables, busbars and connectors, feedback filtering and, in the case of flow batteries, charging and discharging cycles similar to energy storage. Additionally, it is often desirable to employ DC generation with either other sources or storage, or both, so voltages need to be matched.

Both energy storage and electrolytic generation systems could significantly benefit from improved, more granular power management, however, tradeoffs at the system level are required based on the increased size, cost and complexity of additional power electronics. Commercially available devices capable of meaningful improvement in the performance and life of energy storage and electrolytic DC generation are expensive, heavy and require active cooling in the form of fans or pumped water. There are no commercially available products or combination of products that can satisfy these DC systems' requirements of efficient high voltage boost from variable low voltage input, high current handling capability, bi-directional (charging/discharging) operation and isolation from grid and line harmonics in a cost effective, small and lightweight, passively cooled package to make it attractive at a stack, short string level.

Starting with these requirements and the goal of providing a cost effective solution that improves performance and life, drives the architecture and technology selection. With the high boost and current handling capability as guiding requirements, the Combined Energies team selected an H-bridge, delta-wye power topology that allows the incoming DC current to be shared across multiple channels, inverted and voltage-boosted in interleaved transformers. The interleaving realizes a doubling effect of the transformer windings (e.g., 1:2 windings provide a 4X boost) enabling a reduction in transformer size as well as weight. After the boost, the power is rectified and recombined.



Even a few years ago, this topology would be of prohibitive size, weight and cost. Wound, toroidal transformers and IGBT-based switchgear would have driven large, table-top sized designs, mounted on liquid-cooled cold plates. However, the commercial introduction of silicon-carbide switching devices and planar transformers radically shrink this to a printed circuit board-sized package with unparalleled flexibility and conversion efficiencies. As described in US9413271, US9906039 and US10404071, Combined Energies has introduced a first of its kind, power electronics solution for energy storage and electrolytic DC generation systems. The ability to cost effectively integrate, at the stack or sub-string level, a power management board that maintains steady, programmable high voltage DC output, enables bi-directional charging on the same circuit, provides galvanic isolation from the line or grid and is passively cooled gives storage and generation system designers a platform of enabling technology that can boost performance by 30% and double the life of their devices.



Early partners in the commercialization of this technology have been flow battery designers. Combined Energies' power conversion systems are ideally suited for flow batteries, creating efficient integration of their output power with high voltage equipment and enabling their charge and discharge cycles using the same power circuit, greatly simplifying installation and operation. In 4Q21, the team began an integration exercise with a leading flow battery developer with the goal of connecting the partner's flow battery products to a commercial inverter and demonstrating prime power operation for a large data center. The developer had been unable to find a solution that could handle the high current and variable, low voltage DC output of their stacks and efficiently boost them appropriately for a commercial inverter. Additionally, the developer was interested in exploring a long-term integration of an optimized version of the technology.

Combined Energies supplied their flow battery partner with three customer evaluation prototypes. The prototypes are configured with individual enclosures for safe customer handling and evaluation and operated in parallel. The customer evaluation units each had the following specifications: 8kW max, 95 amps, 10-130 VDC input, 6.6X max boost, 66-650 VDC output, with serial communications.

Being input and output current limited, the evaluation units are capable of passing 8kW of power under max input voltage and boost conditions and can handle less power as amperages increase. The technology platform can be tailored to almost any power and boost conditions up to approximately 20kW building blocks. After this, mechanical considerations make the topology less attractive as currently available switches and transformers can no longer be board-mounted. Because of voltage and amperage requirements, the partner requested three customer evaluation units to conservatively meet their 12-15kW load. Upon receipt, the partner successfully mounted and connected to the systems, exercising them with a power supply and load bank to verify their performance according to their proposed test protocols. After reviewing the test performance, the flow battery developer requested a software upgrade that opened their voltage operating window and decreased the response time to a reduction in power or a trip. The Combined Energies team provided this remotely and the partner successfully flashed the upgrade and retested the systems.

The three systems subsequently performed well and connected the variable low voltage output of the flow battery to the commercial inverter during the simulated data center power operation. Start/stop, power ramp, max power and min power runs and trip/restarts were all verified. The units successfully operated passively cooled. As of this writing, the team is evaluating next steps in integrating Combined Energies technology platform into the data center application.