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COMPATIBLE POWER CONVERTERS FOR LITHIUM BATTERY SYSTEMS (EXTENDED ABSTRACT)

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Introduction

There will be applications where the output voltage of a lithium battery cannot be used directly. The powered equipment may need a higher, lower, or better regulated voltage, multiple voltages, or isolation from the battery. In these cases a voltage regulator or converter will be required.

The converter will usually need to have both a high efficiency and high power density to avoid compromising system size, weight, and operating time. Present state-of-the-art converters can achieve efficiencies of 80% - 95% with power densities of 16 - 100 W $(\text{cu. in.})^{-1}$ (1 - 5 W cm^{-3}) depending on input and output voltages, power levels, and need for isolation.

These performance levels typically require power conversion frequencies of the order of 1 MHz, and there are, as yet, very few standard products which might be suitable; a custom design will usually be necessary. The design and construction of these converters has become quite sophisticated, and is usually left to the specialist.

However, the battery system designer can significantly enhance system cost and performance by understanding the technical capabilities, limitations, and compromises inherent in various power conversion circuits. The designer will need to specify the converter performance required carefully and, after considering system variables such as converter input (battery) and output (system requirement) voltages, output power, and duty cycle, thermal considerations, and size, weight, and noise limitations, provide the converter designer with all necessary technical information.

High efficiency d.c.–d.c. converters typically operate by chopping the input to produce an a.c. voltage whose average value is controlled by a variable switch duty cycle. The a.c. is rectified back to d.c. and filtered to remove the chopping frequencies while passing the controlled d.c. component. Various regulator circuit configurations (called "topologies") can raise (boost) or lower (buck) the input voltage, or do both (buck–boost). An optional transformer can be used to provide input–output isolation, or to raise or lower the a.c. voltage further before rectification and filtering. High frequency chopping is used to minimize the size of the, usually, bulky transformer and filters. This type of power conversion has several important characteristics which must be considered in their use.

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Electrical noise and interference

The chopping tends to leave residual ripple voltages and currents on the converter input and output, and generates rapidly changing electric and magnetic fields. This conducted or radiated Electromagnetic Interference (EMI) can impair the operation of the system or nearby equipment, and must be reduced to suitable levels by converter design. Requesting much lower noise levels than the system can actually tolerate, however, will increase the size, weight, and cost of the power converter unnecessarily.

Any efficient regulator necessarily has a negative input impedance at low frequencies. This is easily understood; at any given load output, power is constant, and so must the input power be if efficiency is to remain high. A constant input power causes the input current to drop as the voltage rises, and *vice versa.* If there is sufficient inductance in the input leads or cell construction, it can be driven into oscillation with the converter input filter capacity by the negative input impedance. The highest battery and feed line inductance (and lowest resistance) must be specified to allow the converter designer to avoid this problem.

Converter types and characteristics

The cost, efficiency, size, and weight of a converter will depend on its requirements. Basic buck and boost regulators have the highest performance and lowest cost. Buck regulators provide an output voltage which is less than the battery input, can limit current in the event of a system fault, and are easy to control with a fast and stable response to load changes. Boost regulators generate a voltage greater than the battery voltage, but cannot limit output current and have slower response to load changes. Output voltage polarity for both types is the same as the input polarity, but either polarity may be the system common.

Various buck–boost regulators can provide an output voltage above or below the battery voltage. For example, a regulated 12.0 V d.c. may be obtained from an 8 - 20 V d.c. input. These regulators can be designed to limit current, and can be made with an output voltage of the same, or opposite, polarity as the battery. The internal component stresses and losses are characteristically twice that of buck or boost regulators, resulting in some compromise in efficiency and other performance parameters.

The performance of all regulator types is highest when the output voltage magnitude is close to that of the input. Within limits, multiple output voltages can be obtained from regulators, usually by transformer coupled windings on the main filter choke. These auxiliary outputs should have lower output power than the main output to maintain regulation, which will typically be ±5% - 10% *versus* ±1% or better for the main output. Improved regulation, separate adjustment of each voltage, or individual current limiting requires post regulators on auxiliary outputs, or separate regulators for each output, which will increase overall size and cost.

A d.c.–d.c. converter is required when input/output isolation is necessary. Current limiting is available with most types, and two or more isolated outputs can be provided, of any polarity, with similar considerations as multi-output regulators. Component loss and stress is again twice that of buck–boost regulators, or four times that of buck or boost topologies under similar conditions which, with the need for isolated output sensing and more complex logic, further compromise cost and performance.

An exception occurs when the input–output voltage difference of a regulator is greater than about 4:1. Under these conditions the regulator performance will have degraded to the point where a transformer-coupled-converter can be smaller and more efficient.

It is possible to generate a bipolar (a.c.) output voltage with either two quadrant operation (current same polarity as the voltage) or four quadrant operation (bidirectional power flow). Alternatively, voltage polarities may be fixed but current (and power) flow can be controlled in both directions (*i.e.*, for battery charging as well as discharging). Each added capability, however, requires more and larger semiconductors, with the attendant increase in size, weight, and cost, and decrease in efficiency.

Load considerations

A fixed load is the best condition for a converter, since performance can be optimized for that load. The worst load requirement, unfortunately common in battery applications, is periods of high load interspersed with long durations of very light loads, particularly if the converter energy loss must be minimized during light load conditions. If the duration of the heavy load is long or unknown, then efficiency is also important at the heavy load condition.

A high conversion frequency is necessary to deliver high power from a small converter, but high switching frequencies cause efficiency to drop dramatically at light loads where efficiency is most critical. The usual solution is to use a variable conversion frequency, high at peak load demands and much lower at light loads. The principal drawback is the difficulty in keeping output ripple low at light loads when the energy is being delivered in widely-spaced pulses.

The output voltage regulation specified should be no greater than necessary, and it is better to put the converter near the load, to minimize lead resistance and inductance, rather than to use remote sensing. Output remote voltage sense leads are prone to noise pickup, which can be amplified and applied to the output. The speed of voltage control must be reduced due to delays in remote sensing, which lead to poor response to sudden changes in load current. Lead inductance effects cannot be overcome at all by remote sensing. If the powered system must be remote from the converter, it will usually be necessary to install a high quality filter capacitor either at the powered equipment input terminals or internal to the equipment.

Current limiting

The practical value of output current limiting is only in the protection of the converter and/or battery from damage due to lead or system faults, and to limit the degree of destruction in the powered system. Current limiting will *not* protect electronic equipment from failure in the first place; the powered equipment has already failed by the time current limiting is called upon. Similarly, replacing blown fuses without first repairing equipment usually furthers the extent of the damage.

Thermal considerations

Even very efficient high density converters generate significant heat in a small volume, and heat removal must be considered. As an example, mounting a converter in a plastic case with the batteries is not desirable, but is often unavoidable; a thermally conductive "heat spreader" along an exposed face is advised. Efficiency is of utmost importance when heat removal is limited.

Conclusion

When a power converter is needed in a lithium battery system, the designer should communicate with the intended converter designer or supplier early in the design cycle to optimize system performance and minimize expensive redesign and delays.