Understanding ultracapacitors' role in energy harvesting

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The internal combustion engine has remained dominant in the automotive industry because it has very high energy density (petrol) and very high power density, controlled by the rate of fuel ignition. This combination of energy and power density does not exist for batteries or fuel cells, and alternative power sources have been largely ignored due to their expense. Yet, numerous alternative power sources, including ultracapacitors exist changing the way automotive engineers interface with power sources.

An obvious alternative power source is the battery, but the size and weight of batteries required for an all-electric car makes them impractical. The next-best approach is a hybrid power plant, a power plant that uses a small internal-combustion engine (ICE) in concert with a battery pack. It is fair to say that hybrid power plants have come a long way in the last five years; however, they still leave a great deal to be desired.

The beginning

Early efforts to better energy efficiency in automotive design have proven valuable but are just the beginning. Automotive engineers began by reducing the gross weight of an automobile, replacing metal trim molding with lighter composite materials and by using lighter metals when possible, such as replacing copper-core radiators with aluminum-core radiators to use energy as efficiently as possible. As computer-control mechanisms and sensors became more sophisticated, fuel-injected systems were developed that increased engine performance and fuel efficiency. The early efforts to make more fuel-efficient automobiles focused on how to squeeze more useful energy out of the internal combustion engine.

For batteries and fuel cells to become attractive to engineers, their overall performance must be increased. Petrol has been valued for its energy density on the order of 45MJ/kg while batteries are, in most instances, more than an order-of-magnitude less energy-dense, with energy densities on the order of a fraction to a few MJ/kg.

While ultracapacitors store a large amount of charge, they are still well below the energy density of storage batteries. Batteries in general will have 10 to 30 times the energy storage of ultracapacitors of comparable masses. There are not many situations in which an ultracapacitor solution can replace a battery outright; however, since ultracapacitors have a much lower internal resistance and much faster charge rate than batteries, they can make a battery-powered system run much more efficiently. An array of ultracapacitor cells in series coupled to a load in parallel with a storage battery creates a hybrid power source with higher power and energy density than either device in a stand-alone configuration.

While not a total solution to the problem, the use of ultracapacitors offers a partial solution. Pairing a capacitor with a battery will improve the power density of hybrid supply, which has the added advantage of allowing the battery to operate without seeing large current spikes that would be present without the capacitor. The ability to prevent the battery from experiencing these large current spikes under load allows the battery to have a longer effective life.

A typical starter battery, for example, will degrade very quickly if it is required to supply high current for any length of time. So-called deep cycle batteries are designed specifically to supply higher currents, but even such batteries, with their thicker lead plates, are not immune from damage due to repeated deep cycling. A parallel configuration of a battery with an ultracapacitor can dramatically reduce current drain of the battery under heavy load conditions and thus extend the life of the hybrid power supply as well as providing a more efficient supply.

Traction batteries are specifically designed to be deep cycle; typically, a traction battery will tolerate 80 percent DOD (Depth of Discharge). The rate of current draw can, however, adversely affect the battery's life if it is continually subjected to very high current draw, with the resultant internal heating that can shorten battery life. The addition of the ultracapacitor bank reduces the magnitude of the current draw and thus prevents excessive internal heating of the battery.

In order to quantify the increase in power density derived from pairing an ultracapacitor with a battery, it is essential to recognize the increased power is fundamentally due to the low effective series resistance (ESR) of the ultra cap vs. that of a lead-acid storage battery in this case. In general terms, batteries have higher internal resistance than the ultracapacitor, and by configuring the two sources in parallel, the effective internal resistance of the power source is decreased.

If one considers such parallel combinations and calculates the power delivered to a load that matches the internal resistance of the source, a maximum power transfer curve can be generated as a function of capacitor ESR, which is an indirect measure of the increased power density of the system. This analysis only applies when the capacitor and battery have nearly equal voltage levels; however, when a more complete analysis is applied it is found that, for a short-duration power demand, the deep cycling of the battery is significantly reduced. The duration of the decrease in power from the battery depends on the total energy in the ultracapacitor bank and must be determined on a case-by-case basis.

The graph in **Figure 1** shows the power delivered to a load that matches that of the source assuming a source potential of 1V, the battery internal resistance fixed at 10mΩ and the ultracapacitor ESR in mΩ is plotted on the x-axis.

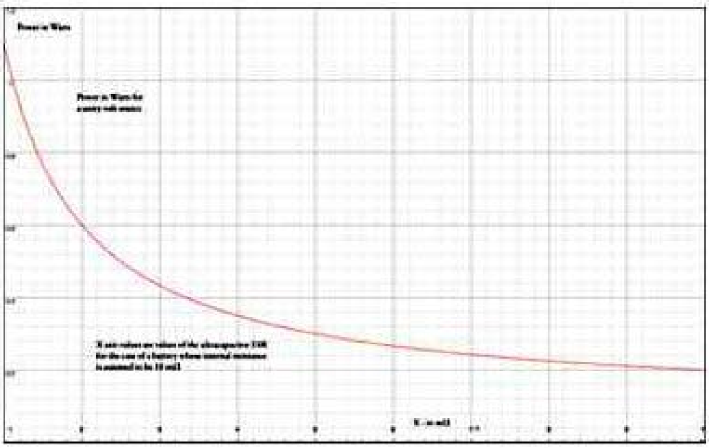

Figure 1: Shown is the power delivered to a load that matches that of the source assuming a source potential of 1V, the battery internal resistance fixed at 10mΩ and the ultracapacitor ESR in mΩ is plotted on the x-axis.

The maximum power transfer for an ultracapacitor bank whose ESR is 1mΩ is 1.1W and drops to 0.2W when the ESR of the capacitor bank is the same as the battery.

There is, however, more to the story. In most instances, it is necessary to construct a "smart" supply; generally speaking, it is necessary to do more than just connect a battery in parallel with an ultracapacitor and hope for the best. The typical ultracapacitor has a voltage rating of only 2.5V to 2.7V and for higher voltage applications the capacitors must be configured in series strings for higher voltage stand offs.

For example, an automotive application consistent with a nominal 12V system would require six ultracapacitors in series for a 15V stand off, which is necessary since voltages at that level are used for charging the battery, and it also provides design margin. As voltage requirements rise, a series configuration may not be the most economical approach. In some instances, it makes sense to use a DC/DC converter, taking advantage of the boost characteristics of a switch-mode power converter. In addition to the use of the many topologies available for power conversion using switch mode circuitry, a microprocessor controller may be necessary.

For example, in a hybrid power source it is often desirable to disengage the ultracapacitor bank from the main power bus, or it may be desirable to monitor voltage levels on the buss and be able to disengage the capacitor bank in the event of a surge voltage on the buss, to prevent damage to the capacitor bank. Obviously, the specific application will dictate the details of what is required.

The techniques available today include the construction of a capacitor matrix to achieve voltage stand off requirements (series string), overall required capacitance (parallel strings), the inclusion of switch-mode circuitry for DC/DC, DC/AC, or other combinations, and the control circuitry, most of which is microcomputer based.

The use of ultracapacitors in regenerative braking systems is a good example of the importance of controllers and other ancillary circuitry. Ultracapacitors are used to harvest the energy that would otherwise be wasted as thermal energy in the process of braking.

The brakes are now more complex in that the braking mechanism will in general consist of two parts; the electric brake and the mechanical brake. The electric brake is a generator, either AC or DC, that charges the capacitor bank. If an AC generator is used, a converter would have to transform the AC signal to a DC signal to charge the bank during the braking procedure. Once the capacitor bank is charged, its energy can be used to accelerate the care from rest. Again, choices have to be made with regard to how to best utilize the energy stored in the capacitor bank to accelerate the automobile.

The specifics of the system will be dictated by many factors such as the choice of electric drives used and many others. This particular example should make it clear that in order to achieve the best performance from ultracapacitors converters and controllers must be included in the design to optimize performance.