Supercapacitors For Load-Levelling In Hybrid Vehicles

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Introduction

There is increasing interest world-wide in the use of so-called "hybrid vehicles" for improved fuel economy, lower emissions and sustainable energy use. Hybrid vehicles are difficult to define but can be broadly described as vehicles that use a combination of technologies for power generation and energy storage. In particular, parallel and series hybrids are widely discussed and consist of an auxiliary power unit (APU) mechanically connected to the driven wheels or with no direct mechanical connection respectively. Series hybrids offer significant advantages over parallel hybrids, such as mechanical simplicity, design flexibility and modularity allowing easier incorporation of technological advances (Gosden, 1996). Hybrid electric vehicles (HEV) are now under development in many countries (Lovins, 1997).

Energy storage is a critical component of any hybrid vehicle. The options for energy storage include batteries, supercapacitors, flywheels and hydraulic devices. Batteries can provide high energy density (eg Li-ion up to 100Wh/kg, Pb-acid 25 Wh/kg) but only relatively low power density (eg 300 W/kg for commercial Pb-acid). Flywheels are still under development and require some significant technological advances before their widespread use can be envisaged. Supercapacitors are the only technology available today that can provide high power capability, ie over 1kW/kg, with long life at reasonable cost. Supercapacitors also have other features that make them attractive for use in hybrid electric vehicles such as their ability to be used for regenerative braking (energy efficiency), maintenance-free operation, high electrical efficiency and low toxicity with easy disposal.

Supercapacitors

Supercapacitors utilise the capacitance created when an electrode is in contact with an electrolyte. This capacitance arises from the formation on the electrode surface of a layer of electrolyte ions (the "double layer"). By choosing and fabricating electrodes with extremely high surface area (eg 1000 m^2/g or greater), very large capacitances are achievable. Current technology allows a 4000 Farad capacitor to be constructed in a container the size of a beer can. As these are electrochemical devices, their voltage limit is low, between 1-3 V, however higher voltages can be achieved by serial connection similar to batteries.

The critical characteristics of a supercapacitor are its energy density (Wh/kg) and power density (W/kg). The energy density is dependent on the capacitance and maximum voltage, while the power density is dependent on the equivalent series resistance (esr) and maximum voltage. A survey of the small number of commercially available devices reveals a maximum energy density of about 5 Wh/kg and power density of over 1kW/kg. The energy density of capacitors (and batteries) decreases with increasing power, because of i^2r losses arising primarily from finite internal resistance. Their specific power and energy interrelationship is conveniently shown in a Ragone plot (Figure 1). As is evident from the figure, when the time-scale of power delivery is in the range 0.4 - 40 s supercapacitors are the technology of choice. Power delivery for vehicle acceleration falls within this range.

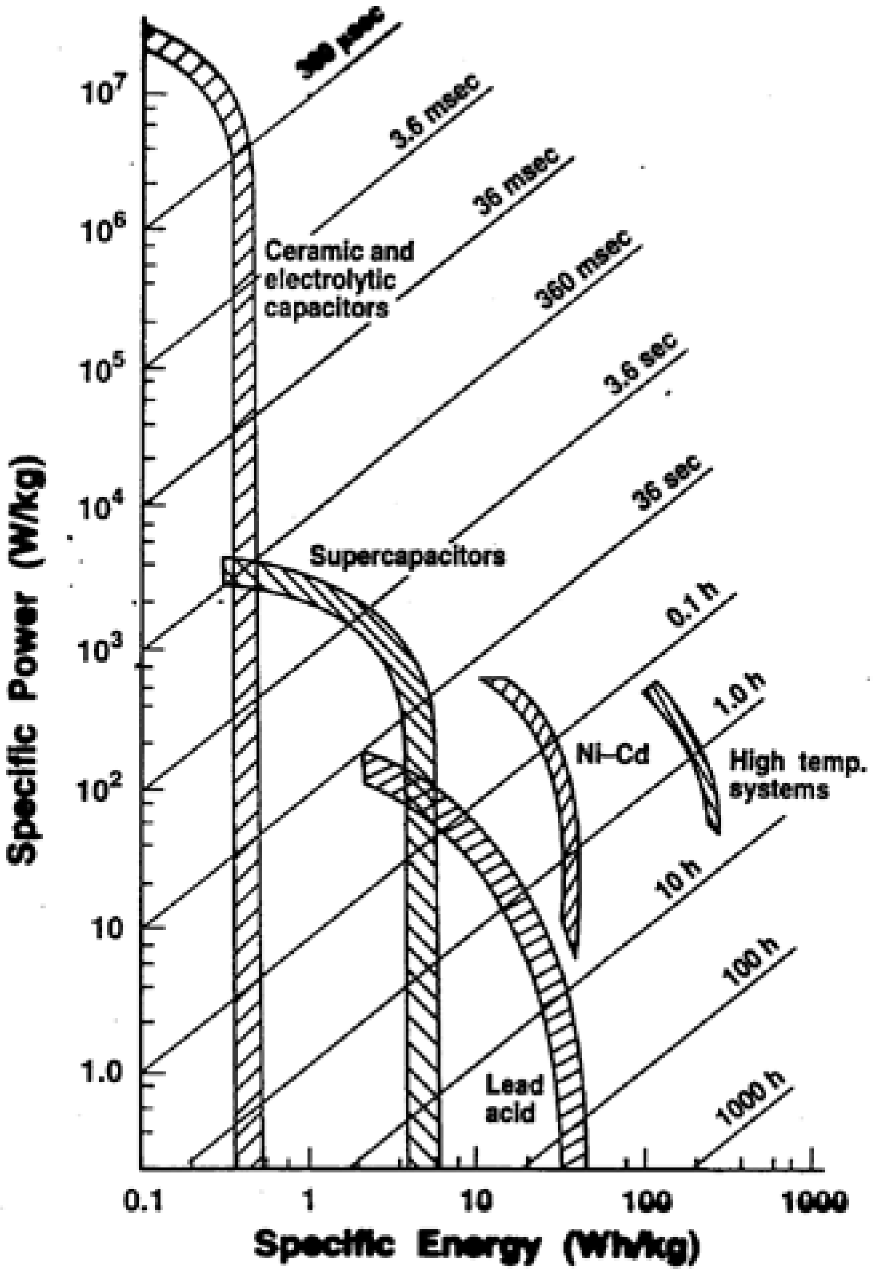

Figure 1. Ragone plot for capacitors and batteries

Supercapacitors for impulse power in hybrid vehicles have a number of attractive characteristics:

- being an energy storage device that does not rely on electrochemical energy conversion, results in very high cycle life (>10^4) even at high depths of discharge (eg 90%).
- electrical efficiency is high, typically greater than 90% under high power conditions.
- their very high power capability allows for efficient regenerative braking as well as rapid acceleration.
- their state of charge is instantly known through their voltage, although this characteristic does require slightly more complex power electronics to match voltage levels to the power unit.

Other issues such as energy leakage rates and cell balancing in high voltage series packs are being addressed, with cost the only barrier to more widespread use.

Supercapacitors in Hybrid Passenger Vehicles

The characteristics of a HEV supercapacitor depend critically on the vehicle mass, its desired performance and driving cycle, and on the characteristics of the main power unit, which could be an internal combustion engine, fuel cell or other technology. Driving cycles such as the USA FUDS (Federal Urban Driving Schedule) or the related Australian Standard AS 2877 define vehicle speed during a time period and can be used to calculate instantaneous and average power once the vehicle characteristics are defined. Moore (1996) has published a detailed analysis of the energy and power requirements of a conceptual hybrid vehicle with a mass of 846 kg. Using reasonable assumptions for rolling resistance, aerodynamic drag, hill climbing ability and driving cycle, Moore (1996) calculates that the load-levelling device provides a peak power of 36 kW and stores 1.1 kWh of electrical energy, (with an all up weight of 42 kg) although these figures are chosen for state-of-the-art Pb-acid batteries and not optimised for capacitors. This vehicle is based on the use of a 28 kW fuel cell and includes regenerative braking and can accelerate from 0-100 kph in 8.5 s or 7.1 s with a 5% grade.

Using a higher power supercapacitor of similar weight but rated at 50 kW will reduce these acceleration times to 6.6 and 5.7 s respectively, but only provide enough energy for one acceleration before needing to be recharged. At 100 kph, the excess power from the fuel cell is calculated to be 21.3 kW on the flat or 9.75 kW on the grade. With this power level available, the supercapacitors will recharge to 90% state-of-charge (SOC) in 26 s on the flat or 56 s on the grade (assuming 90% efficiency).

The issue of the reserve capability of the supercapacitor power unit needs to be addressed for local circumstances, such as geography, drive cycle and APU type, however in most circumstances only sufficient energy for one or at most 2 full power accelerations needs to be stored. This is a result of the efficient capture of the energy from braking which in effect uses the vehicle's kinetic energy as a storage system. Clearly the need for extra energy decreases to zero as the vehicle speed reaches a maximum, however some storage capacity is required to capture the converted energy during deceleration. In those circumstances where the vehicle's speed is reduced without braking, for example coasting to a stop on a grade, the APU will be charging the supercapacitor at full power during the slow-down and provide a full SOC ready for acceleration back up to speed.

The specifications of such a supercapacitor (assembled from a number of individual cells) built using current technology and based on a voltage window of 400 to 200 V include:

characteristic	total	individual cells
voltage max (V)	400	3.0
current max (A)	1400	
current av (A)	178	
capacitance (F)	4	495
esr (ohms)	0.143	0.0011
weight (kg)	44.6	0.33
cells	1	135
power av (kW)	51	
power max (kW)	286	
efficiency[1] av (%)	86	
energy total (kJ)	300	
energy useable[2] (kJ)	226	
energy density[3] (Wh/kg)	1.4	
power density (kW/kg)	6.4	

1 at 51 kW level

2 discharge to 0.5 V_o

3 useable energy

Leakage is not considered a problem over the time-scales involved (ie hours not days), however no de-rating factor has been applied to compensate for cell-to-cell variation arising from a spread of capacitance, esr, leakage or thermal gradients during high power operation (Miller, 1994).

Supercapacitors for Hybrid Buses

The incorporation of supercapacitors into hybrid buses is more advanced than that for passenger vehicles. The USA National Aeronautical and Space Administration has constructed a bus using a 400 V, 1.59 MJ supercapacitor for load-levelling, however performance details are still unavailable.

References

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