



WHITE PAPER

ULTRACAPACITOR ASSISTED ELECTRIC DRIVES FOR TRANSPORTATION

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Introduction

Vehicle introduction of electric drives has primarily been for traction applications having power ratings of 30 kW to 60 kW and higher for hybrid and battery electric vehicles. Power train electrification on the other hand has lagged due to fierce price constraints exacerbated by the need for dual voltage networks to support both existing electronics and future higher power functions. Traditional solutions based on the use of a second battery are generally unable to make a business case for acceptance. Therefore it is necessary to explore in greater depth the option of distributed power modules based on ultracapacitor energy storage.

This paper investigates the merits of distributed energy storage modules for electric drive subsystems required when steering, brakes and engine control are electrified. The distributed module concept is then extended to the case of ISG mild hybridization to achieve electrical distribution system (EDS) stabilization. The very high values of P/E for ultracapacitor local energy storage with a modestly sized dc/dc converter interface to the EDS is shown to significantly improve functional performance while mitigating EDS voltage fluctuations.

Where do ultracapacitors fit in?

Capacitors are broadly classified as being electrostatic, electrolytic, or electronic double layer by virtue of the medium that sustains the electric field between a pair of electrodes. Figure 1 is an illustration of these three categories of capacitors viewed from their physical construction and physics of energy storage.

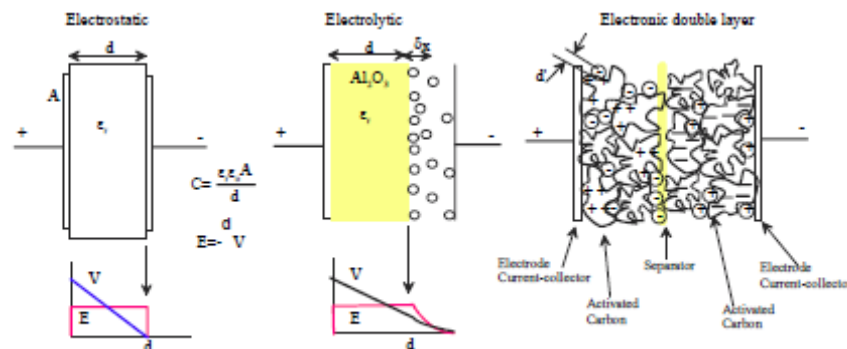


Figure 1: Capacitor categories

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The electrostatic capacitor is generally constructed of metal films, ceramic, or glass, mica or other dielectric material. Metal film capacitors are popular in high frequency applications for which multi-layer polymer, MLP, types are typical [1]. Ceramic types such as multi-layer ceramics, MLC's, are popular as surface mount devices for electronics assembly. The electrostatic capacitor in Figure 1 consists of two metal electrodes separated by a dielectric of thickness, d . A potential across the two metal electrodes creates a uniform electric field in the insulating medium the properties of which determine the voltage rating.

An electrostatic capacitor is similar to the electrostatic unit in construction except for the presence of a conductive electrolytic salt that is in direct contact with the metal current collector, or cathode. The anode is made from an etched, anodizable, metal foil that is formed by application of an electric potential when the foil is immersed in an electrolyte during manufacture. An electrolyte different from the forming electrolyte is used as the ionic conductor. When the formed anode foil with its alumina dielectric layer is rolled up along with the cathode foil, an insulating separator such as Kraft paper is placed on the outside of the anode foil to insulate it. The negative foil is typically the outside of the electrolytic can.

When an external potential is applied across the electrolyte terminals, a uniform electric field is established across the anodized layer of alumina while a decaying electric field exists some distance, δx , into the electrolyte according to Poisson's equation. Because of the presence of an electric field that extends into the electrolyte, this capacitor will have a more limited breakdown voltage than an electrostatic capacitor. When the electrolyte breaks down due to over potential it can lead to short circuit failure. Electrolytic capacitor manufacturers design for breakdown voltages somewhat above the surge rating of the unit. Typically, higher surge rated electrolytics also have higher resistance, hence a higher equivalent series resistance, ESR, and therefore higher losses in power electronic circuits. Another consequence of an electric field in the electrolyte is the fact that capacitor current is now a function of both voltage change and capacitance change as a function of voltage or:

$$i = \frac{d(CV)}{dt} = C \frac{dV}{dt} + V \frac{dC}{dt} \quad (1)$$

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As a result of the electrolyte change for higher operating voltages, the electrolytic capacitor has a nonlinear voltage characteristic:

$$V(T) = 550 (1 - \gamma (T - 65)) \quad (2)$$

where $\gamma=4.16$ and $T < 125^\circ\text{C}$.

The energy density of high voltage, mylar, electrostatic capacitors is theoretically 4.34 kJ/kg under an impressed electric field of 6.5×10^8 V/m. For electrolytic capacitors the energy density is generally 1.5 kJ/kg and theoretically less than 8 to 12 kJ/kg. These capacitors have specific power density capability of 500 kW/kg and higher but for discharge times of only microseconds. Electronic double layer capacitors, DLC, or ultracapacitors, were first developed and patented in 1961 by SOHIO. The construction of a DLC consists of a pair of metal foil electrodes, each of which has an activated carbon, AC, fiber mat deposited on metal foil. The activated carbon side of each electrode is separated by an electronic barrier such as glass paper then sandwiched or rolled into a package. An aqueous or organic electrolyte salt impregnates the activated carbon as shown in Figure 1. The electronic properties of a DLC are strongly dependent on the porosity of the activated carbon and on the molecular size of the electrolyte ions. Activated carbon electrodes used in DLC's have specific surface areas of 1000 to 2300 m^2/g and charge separation (Helmholtz) distances on the order of 10 Angstrom or less. The charge separation distance δx extends from electronic charge in the AC mesh to at minimum one half the ion molecular diameter and at maximum to several ionic molecular layers into the electrolyte [2].

Referring to Figure 1, during charging the electrolyte anions and cations are drawn to electrodes of opposite polarity where they accumulate into layers inside the AC pores with a distribution governed by pore size. When charged, the electrolyte becomes depleted of ions. Electrochemical investigations have shown that AC pore sizes range from nano-pores with pocket diameters <1nm, to micro-pores with average pore diameters of 1.5 to 3.0 nm. Ion diameters in the electrolyte are on the order of 1 nm so their penetration into pores of lower diameter will be blocked. The morphology of AC suggests that when average pore diameters are 3.0 nm good capacitance values exist for both organic and aqueous electrolytes. When the AC pore size diameters illustrated as pockets in Fig.1 drop to 2.0 nm and below, one can expect good capacitance only for aqueous electrolytes and when below 1.0 nm, essentially no DLC capacitance. Activated carbon pore size and electrolyte anion and cation ionic diameters determine to a large extent the DLC phenomena.

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The voltage rating of DLC's is constrained by the same phenomena of electric field presence within the electrolyte as in conventional metal foil electrolytic capacitors. DLC's with organic electrolytes have voltage ratings of <3.0 V per cell whereas with aqueous electrolytes the voltage rating drops to <1.23 V per cell, typically 0.9 V. In all DLC's the terminal capacitance consists of the series combination of an anode DLC and the cathode DLC, so the net rated voltage is twice the value of the electrolyte decomposition voltage. Organic electrolyte DLC's have higher decomposition voltages and higher specific energy but higher resistance than aqueous types. The low conductivity of organic electrolyte DLC's results in higher ESR. ESR can be reduced in general by the addition of vapor grown carbon fiber to the AC. Improvement of ESR at cold temperatures is achieved by the addition of the solvent acetonitrile, AN, to propylene carbonate, PC, and other constituents of electrolyte. With the addition of AN the ESR is found to increase by less than a factor of 2 at -40°C compared to a 12 fold increase in PC [3]. Commercial ultracapacitors today have specific energy densities of $E=3$ to 5 Wh/kg and specific power densities of $P>1.5$ kW/kg. The specific power-to-energy metrics for various energy storage systems are listed in Table 1.

Storage Technology	Lead-Acid	NiMH	Li-Ion EV	Li-Ion HEV	DLC
P/E	6	2.7	7	36	>700

Table 1: Specific power to energy comparisons

In a capacitive energy storage system the accumulated energy is proportional to voltage squared. Electrostatic capacitor storage systems for photo-flash and defibrillators with operating voltages to 5 kV have specific power ratings of 10^9 W/kg but are able to sustain discharge for only micro-seconds. Ultracapacitors, as we have seen, fall mid-way between electrochemical and electrostatic energy storage systems. In fact, it is true to say that ultracapacitors have 10 times the energy density of electrostatic capacitors and 10 times the power density of electrochemical storage systems. The graphic in Figure 2 illustrates the regions of applicability of the various energy storage systems.

The inclusion of time into the plots in Fig.2 helps illustrate the pulse duration sustainability of the various energy storage systems. Energy density diminishes for increasing pulse power density, and this behavior is charted in Ragone plots as a means to quantify the energy storage system and to size the system for applications ranging from traction drives to energy caches for electrified ancillaries. Energy throughput, or cycling is another important feature of all energy storage systems, and a metric that has often times been overlooked. A metric of Wh-cycles is more descriptive of energy storage system suitability for the various mobile applications.

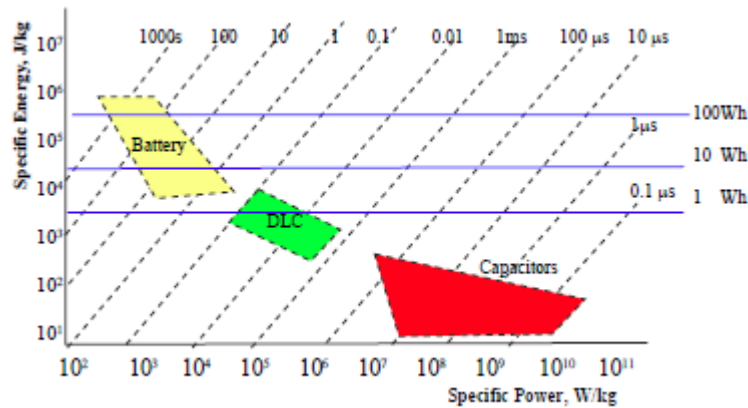
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Ragone plots are used to distinguish between energy storage system capacity in Wh/kg versus their pulse power capability in W/kg. These charts are also used to compare the relative merits of one energy storage technology versus others. Figure 3 is a Ragone chart to which time parametric traces for 10 s, 30 s and 3 minute discharge durations have been added as parameters characteristic of mobile applications. Advanced battery technologies tailored to high energy demand applications such as electric vehicles will typically have a specific energy approximately twice their specific power. Hybrid vehicle batteries on the other hand will have specific power much higher than their specific energy. Table 1 lists the ratio of specific power to specific energy (P/E) of the various energy storage technologies including ultracapacitors. P/E values in the range of 3 are acceptable for EV's whereas HEV's require P/E of 7 or higher to meet the demands of pulse power for vehicle launch and acceleration when a downsized engine is used.

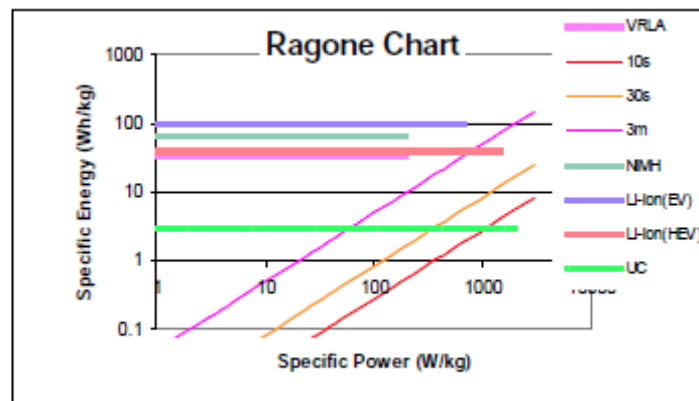


Figure 3: Ragonne chart of common energy storage system technologies

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Pulse duration boundaries of 3s, 10s and 3 minutes in Figure 3 show the discharge power limits for ultracapacitors, UC, and various advanced battery technologies. A 3 Wh/kg UC for example can sustain a 1kW/kg discharge pulse for 3s whereas only the Li-Ion battery is capable of this discharge level, but is able to sustain such pulse powers for nearly 3 minutes.

The capability to sustain discharge power for prescribed time durations as single pulse events or a small number of repetitive events is typical of automotive functions. Examples of such functions include the safety critical subsystems, power train subsystems, body electrical systems, and customer amenities. Safety critical subsystems include electric assist steering, braking, and engine throttle control. Power train subsystems include engine cooling fans, water and oil pumps, transmission oil pump, continuously variable transmission actuator oil pump, catalyst pre-heating, and motor-generators for hybrid functions. Body electrical systems include door, seat, window and many other electrically actuated subsystems. Customer amenities such as electrically driven heating-ventilating-air-conditioning, quick heat for seats, steering wheel and passenger cabin are typical applications that require electrical power.

Safety critical and hybrid vehicle applications

The electrical distribution system, EDS, system for a hybridized vehicle must support its attendant electrified steering, braking and engine control. Because the brand penetration of hybridization today is low relative to more conventional vehicles the wiring for hybridization and ancillary electrification is achieved via overlay harnesses. In typical installations to date there are many issues with EDS related to the burden of these higher power functions. Distributed ultracapacitor modules are one approach to alleviate EDS voltage sag and transients by supplying high peak power locally while demanding only the supply of average power from the vehicle power supply. This essentially decouples the high transient power load from the vehicle power supply system. A further requirement of safety critical applications is the necessity of redundant power supply in the event of loss of the main EDS branch circuit for electric assist steering, electro-hydraulic or electro-mechanical braking, and electronic throttle control.

Figure 3 illustrates an overlay harness design for an integrated-starter-generator, or ISG, hybrid [3]. In this system the electrified ancillaries are supplied via these separate harnesses connected to the vehicle system through expanded or additional power distribution centers. The power distribution centers now in use contain not only branch circuit fusing and protective relaying, but fault and arc detection. With distributed energy storage modules, and possibly dc/dc converter interface to ultracapacitor module, the issues of faults and wiring arcing are mitigated because the high energy sources and loads are decoupled from the EDS. High voltage wiring is shown as red traces, blue traces are under hood components, etc. Protective relay and contactors are necessary for galvanic isolation of the hybrid system energy storage components.

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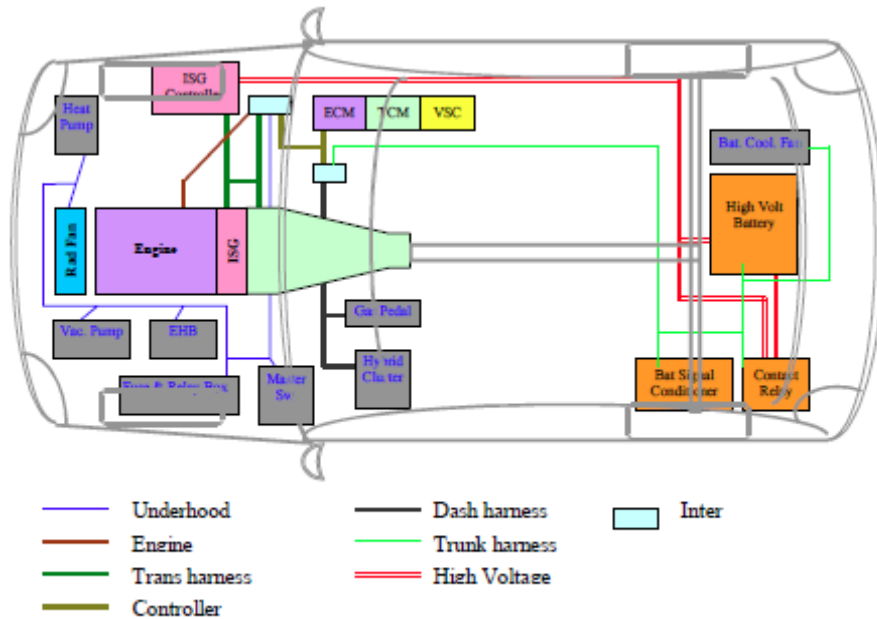
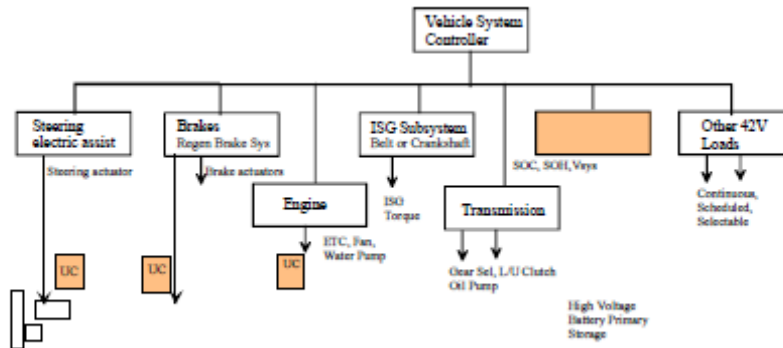


Figure 4: Vehicle electrical overlay harness structure for hybrid functions



performance by delivering pulse power when needed. The situation with brakes is similar; high pulse power from distributed modules provide not only point of load power but redundant energy supply as well. Figure 6 illustrates the components of an electro-hydraulic brake system necessary for hybrid vehicles to realize efficient energy recuperation.

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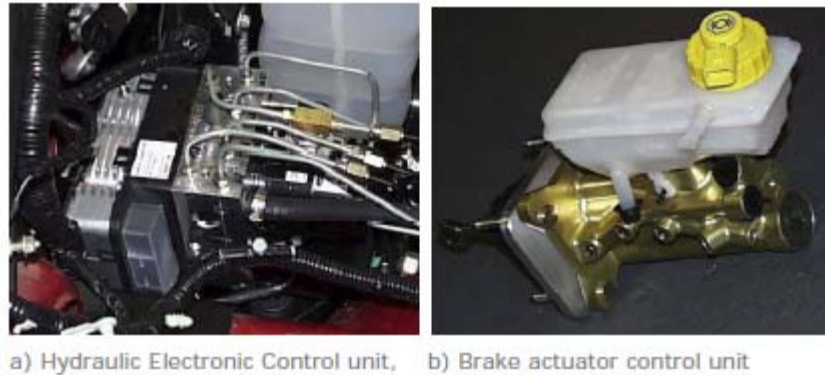


Figure 6: Electro-hydraulic brake system for hybrid vehicles

A distributed energy storage module can be packaged in the series regenerative brake systems hydraulic electronic control unit (Figure 6-a) or at the disc brake calipers in an electromechanical brake system. The distributed module may be configured for parallel boosting as a point of load module or as a cascade boost if located in proximity to the vehicle battery as shown in Figure 7. Long line lengths isolate the remote actuation function from the vehicle power supply.

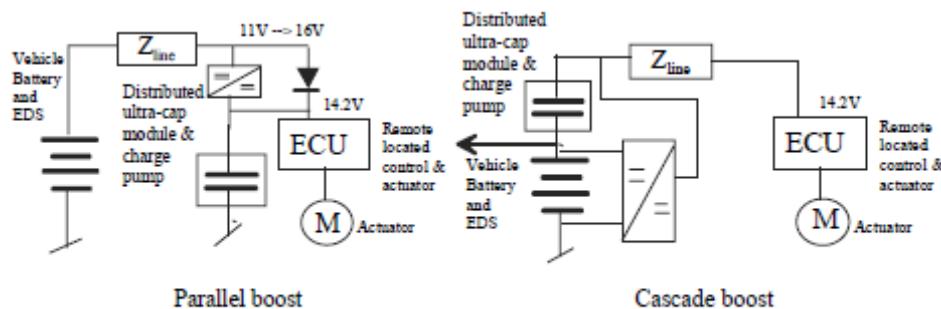


Figure 7: Illustration of distributed energy module locations

B. Power Train Applications of Distributed Modules

Mild hybridization such as belt connected or crankshaft integrated starter alternator (ISA) or generator (ISG) systems are used to implement idle-stop power trains for improved fuel economy. The presence of these bi-directional torque sources in the power train naturally leads to their use for engine boosting and vehicle deceleration energy recuperation. During normal operation of ISG's the EDS remains well within its voltage swing limits. However, during more dynamic driving such as hilly terrain where engine torque augmentation is demanded for

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upgrades and energy recovery is necessary on downgrades the impact on EDS is dramatic as Figure 8 illustrates. High levels of torque assist result in ISG motoring operation during grade climb, particularly when longer final drives are implemented in the vehicle driveline resulting in engine lugging. During hill descent the ISG recuperates as much energy as the traditional battery system can accept, which for today’s advanced batteries is restricted for state of charge (SOC) levels above 80%. This limits energy recovery and hence overall fuel economy. A distributed module with 1kW dc/dc converter is capable of sourcing and sinking all of the ISA power in such dynamic events while completely stabilizing the EDS voltage so that the remainder of the vehicle system operates at nominal bus voltage.

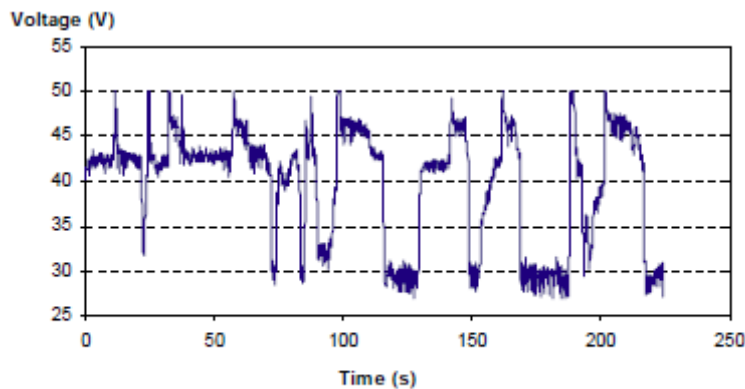


Figure 8: ISG performance in hilly terrain: Boost and Regeneration

Table 2 is an event-by-event accounting of energy flow for ISG operation according to the scenario in Figure 8. The peak regeneration event represents 6.7 Wh or approximately a 1% SOC variation on a 42V, 16 Ah system battery. The peak boosting event requires some 20 Wh or 3% of the battery energy if fully charged. Since the battery will likely be operating closer to 50% these SOC variations are easily doubled. With SOC variations in the range of 5% an ISG designer would find that battery cycle life is seriously reduced, resulting in a need for shorter warranty intervals and provisions for replacement. The distributed module approach, particularly for ultracapacitors having high cycle life (>100k cycles without deterioration), at high SOC, present a very attractive alternative [6,7].

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Event	1	2	3	4	5	6	7	8	9	10	11	Total
Regen	3	1	7.5	8	1	1	12	6	5	4	8	56.5s
Boost	4	4	4	10	10	8	15	4	8	-	-	67s

Table 2: ISG Energy throughput for hilly terrain driving

Figure 9 illustrates the duration of regeneration events for various standard driving cycles. This data can be used to match a distributed module to the vehicle ISG so that power train performance is sustained and the EDS stabilized. Combinations of system batteries and ultracapacitors along with engine driven generators such as ISG and full hybrid are now under investigation [8] as one means to improve efficiency and reduce system weight of on-board energy storage for EV's and HEV's.

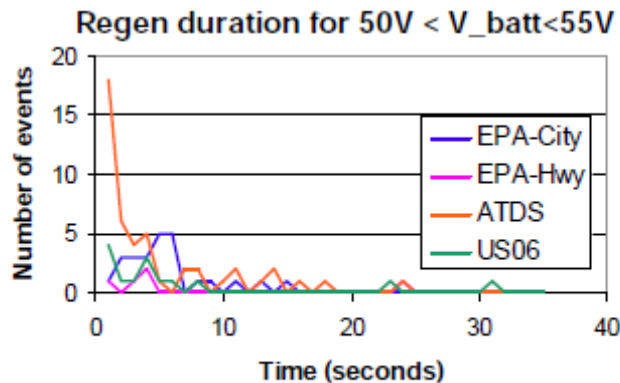


Figure 9: Drive cycle dependence of idle-stop duration

Sizing the Ultracapacitor Distributed Modules

In [2], Mitsui shows that the charge and discharge efficiencies of ultracapacitors under constant current conditions are given as (3). The ultracapacitor efficiency is determined not by internal resistance alone but by how well its time constant matches the expected pulse duration of the application.

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$$\eta_c = \frac{1}{(1 + 2\tau/T)}$$

$$\eta_d = 1 - 2\tau/T \quad (3)$$

where, R_i =ultracapacitor internal resistance, $\tau=R_iC$, and T = constant current charge or discharge duration as illustrated by the experimental testing circuits in Figure 10.

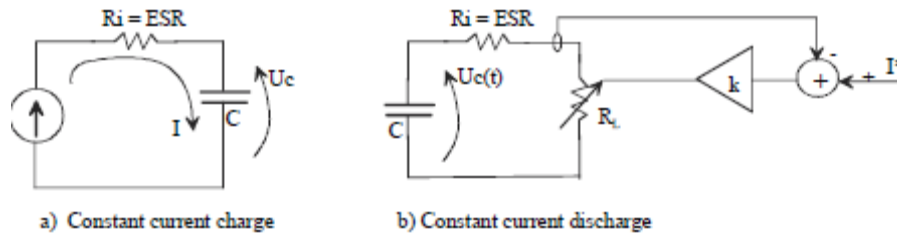


Figure 10: Constant current evaluation of ultracapacitor efficiency

The ultracapacitor time constant and “time” rating are determined using (4) and available specification data.

$$\frac{I}{C} = \frac{V_r}{T} \quad (4)$$

where, T = the constant current discharge time to fully deplete the ultracapacitor stored energy and V_r =the ultracapacitor rated voltage. Representative ultracapacitor specifications are listed in Table 3. Internal resistance used is the dc value since discharge pulse durations will be 3s to 3 minutes to accommodate the vehicle loads of interest.

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DLC	V_r V	I A	C F	R_i m Ω	W_e J	τ s	T s
PC10	2.5	2.5	10	180	31.25	1.8	10
PC100	2.5	25	100	13	312.5	1.3	10
BCAP0015	42	600	145	10	127890	1.45	10.15
BCAP0017	14	600	435	4	42630	1.74	10.15

Table 3: Ultracapacitor specification data (Maxwell Technologies, Inc.)

Where the capacitor characteristic discharge time, T , is calculated with the aide of (4). It is interesting to note from Table 3 that both cells and modules listed are 10-second capacitors. The discharge efficiency of the 14 V and 42 V BOOSTCAP modules are shown in Figure 11 with pulse time, T , as a variable. Note that regardless of voltage, 14 V or 42 V, the two modules have very similar discharge efficiency since τ is nearly the same for both.

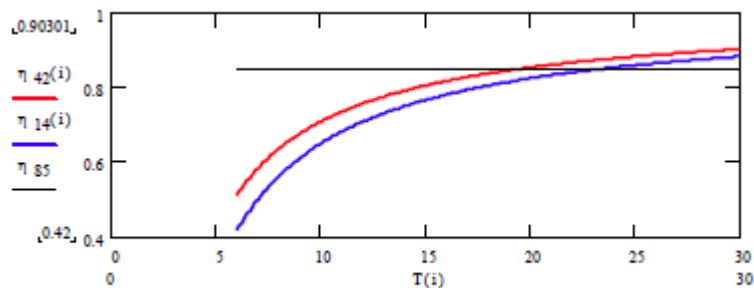


Figure 11: Ultracapacitor discharge efficiency

To hold >85% discharge efficiency the discharge pulse durations must be restricted to $T_{d42}=19.4$ s for the 42 V BOOSTCAP (red trace in Figure 11) and $T_{d14}= 23.2$ s for the 14 V BOOSTCAP (blue trace intersection with 85% efficiency line). Rearranging (4) and solving for current results in discharge currents of <314 A from the 42V module and <262.5 A from the 14 V module. Discharging at these currents for the stated discharge pulse time results in 100% depletion of the capacitor energy. It is common practice to extract 50% to 75% of the total capacitor energy in which case the current magnitudes stated are proper for the “time” rating of the ultracapacitor module. In this case, and using the data available from Table 3 results in available output power of:

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$$P_o = \frac{W_e \eta_d}{T_d} \quad (5)$$

According to (5) the 42 V module is capable of sustaining a load of 5.6 kW for 10 s while maintaining a discharge efficiency of greater than 85%. To illustrate the implementation of this scheme for a distributed energy storage module, the parallel boost scheme depicted in Figure 7 would consist of just the ultracapacitor and its interface converter placed in parallel with the load. The interface converter is necessary in order to maintain the load point voltage during pulse discharging. Some examples will illustrate the implementation of the distributed energy module architecture shown in Figures 4 and 5.

Vehicle system with distributed energy modules

Safety critical loads, electric assist steering, braking, and throttle control are typically short duration, high power loads. Power train functions such as boosting and energy recuperation are medium term loads. Customer amenities such as cabin air conditioning during idle-stop mode of an ISG are long-term events (Figure 9). In Table 4 the pulse power demands and duration of several representative vehicle loads are listed along with the appropriate “time” rated ultracapacitor needed. In Table 4 the ultracapacitor current, I_c , and module capacitance, C , are taken from:

$$I_c = \frac{8W_o}{6\eta_d V_{c0} T} \quad (6)$$

$$C = \frac{8W_o}{3\eta_d V_{c0}^2} \quad (7)$$

where W_o is the ultracapacitor output energy necessary to match the load requirement. In Table 4 the application current is listed as $I_r(A_{dc})$, the module time constant, τ , and internal resistance, R_i . The needed cell capacity is listed in the last column. The data in Table 4 are calculated for a nominal voltage of 42V, a discharge efficiency of 85%, and a module of a single string of 20 cells.

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Load	P (kW)	T (s)	W _o (kJ)	I _r (A)	C (F)	I _c (A)	τ (s)	R _i (mΩ)	C _{cell} (F)
Steer	1.2	3	3.6	28.6	6.4	45	0.23	35	128
Brakes	2	3	6	47.6	10.7	75	0.23	21	214
Throttle	0.1	0.2	0.02	2.4	0.04	3.8	0.015	417	0.72
Turbo	2.5	2	5	59.5	8.9	94	0.15	17	178
E-Cat	3	8	24	71.4	42.7	112	0.6	14	854
ISG-launch	8	10	80	190	142	299	0.75	5.3	2850
ISG-regen	10	5	50	238	89	374	0.38	4.2	1780
HVAC	1.5	180	270	35.7	480	56	13.5	28	9600

Table 4: Distributed energy module requirements

It is indeed interesting to note that the cell ratings for many of these distributed energy module applications are in close agreement with available ultracapacitor cell capacities.

According to Table 4 an ISG system would meet all its launch and regeneration requirements with a single 142 F module (series string of 20 each, 2850 F ultracapacitors). This module would be capable of greater than 100,000 full charge/discharge cycles without loss of capacity and perhaps >500,000 full cycles without exceeding a 20% loss in performance. Also, the module easily meets the peak current requirements of the power train, safety critical, and amenity loads. Cost is a major concern in automotive systems. Ultracapacitor technology has evolved to the point that cells will be available at <\$0.02/F in high quantity (>10,000 piece) by 2005. This cost is quickly decreasing to <\$0.01/F and lower over the next few years. With an ultracapacitor distributed module the vehicle system designer now has the tools necessary to insure full function capability under the most demanding conditions for all vehicle subsystems. Vehicle power supply need only deliver average load power so that circuit protection, wire harness, power distribution centers, and connectors can be made smaller and more durable.

Conclusion

The inclusion of distributed energy storage modules into the vehicle electrical system effectively de-couples subsystem load transient requirements from steady state power delivery. Vehicle safety critical subsystems not only have sufficient local energy to insure that function is not lost in the event the vehicle power supply is unable to meet all loads, but distributed energy modules mean that these loads have a redundant source of power in close proximity to the actuators.

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Hybrid functions such as ISG for idle-stop functionality can be made more durable with a modest amount of distributed energy while decoupling the vehicle energy storage system from high cycling loads.

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