WHITE PAPER

POWER ELECTRONIC INTERFACE FOR AN ULTRACAPACITOR AS THE POWER BUFFER IN A HYBRID ELECTRIC ENERGY STORAGE SYSTEM

Dr. John Miller, PE, Michaela Prummer and Dr. Adrian Schneuwly
Maxwell Technologies, Inc.

Maxwell Technologies, Inc.
Worldwide Headquarters
9244 Balboa Avenue
San Diego, CA 92123
USA
Phone: +1 858 503 3300
Fax: +1 858 503 3301

Maxwell Technologies SA
CH-1728 Rossens
Switzerland
Phone: +41 (0)26 411 85 00
Fax: +41 (0)26 411 85 05

Maxwell Technologies GmbH
Brucker Strasse 21
D-82205 Gilching
Germany
Phone: +49 (0)8105 24 16 10
Fax: +49 (0)8105 24 16 19

Maxwell Technologies, Inc. - Shanghai Representative Office
Rm.2104, Suncome Liauw's Plaza
738 Shang Cheng Road
Pudong New Area
Shanghai 200120, P.R. China
Phone: +86 21 5836 5733
Fax: +86 21 5836 5620

info@maxwell.com – www.maxwell.com

Ultracapacitor power energy storage cells have been introduced into the marketplace in relatively large volumes since 1996 and continue to experience steady growth. In recent years ultracapacitors have become more accepted as high power buffers for industrial, and transportation applications in combination with conventional lead-acid batteries, as standalone pulse power packs, or in combination with advanced chemistry batteries. The merits of ultracapacitors in such applications arise from their high power capability based on ultra-low internal resistance, wide operating temperature range of -40^{o}C to +65^{o}C, minimal maintenance, relatively high abuse tolerance to over charging and over temperature, high cycling capability on the order of one million charge-discharge events at 75% state-of-charge swing and reasonable price. Ultracapacitors today store approximately a tenth the energy of nickel metal hydride batteries but are capable of more than ten times the power. Table 1 illustrates the metrics of ultracapacitors and advanced chemistry batteries. Notice that energy specific cost of the ultracapacitor is high relative to batteries due to its modest specific energy density, but that specific cost of power is just the reverse; for the ultracapacitor "cost of power" is low relative to batteries, regardless of type.

Combining both energy storage technologies together results in an energy storage device with high energy availability combined with high power and high efficiency. This paper examines the recent surge of interest in combining the power dense ultracapacitor with an energy optimized lithium-ion battery and what the interface requirements are for the ultracapacitor in this active parallel configuration.

Maxwell Technologies, Inc.
Worldwide Headquarters
9244 Balboa Avenue
San Diego, CA 92123
USA
Phone: +1 858 503 3300
Fax: +1 858 503 3301

Maxwell Technologies SA
CH-1728 Rossens
Switzerland
Phone: +41 (0)26 411 85 00
Fax: +41 (0)26 411 85 05

Maxwell Technologies GmbH
Brucker Strasse 21
D-82205 Gilching
Germany
Phone: +49 (0)8105 24 16 10
Fax: +49 (0)8105 24 16 19

Maxwell Technologies, Inc. - Shanghai Representative Office
Rm.2104, Suncome Liauw's Plaza
738 Shang Cheng Road
Pudong New Area
Shanghai 200120, P.R. China
Phone: +86 21 5836 5733
Fax: +86 21 5836 5620

info@maxwell.com – www.maxwell.com

Table 1 Energy Storage Component Attributes

ESS Component	Specific Energy (Wh/kg)	Energy specific cost ($/Wh)	Power specific cost ($/kW)	Cycle Capability at 80% DOD # Cycles (Wh-cycles)
Ultracap	5	16	12	$>10^6$ $4x10^6$
VRLA	30	0.12	80	$3*10^2$ $7x10^3$
NiMH	44	0.65	75	$4*10^3$ $1.5x10^5$
Lithium	70	0.50	75	JCS $2.5*10^3$ $1.4x10^5$ A123 $5*10^3$ $2.8x10^5$ AltairNano $15*10^3$ $8.4x10^5$

The ultracapacitor, in very simplified terms, is the series combination of two double layer capacitances, back-to-back in the same package to form a capacitor. Figure 1 illustrates the electronic equivalent representation of the ultracapacitor as a series RC network where the resistance elements model the electronic (Re) and ionic (Ri) components of total internal resistance, also described as equivalent series resistance, ESR. Each electrode of the ultracapacitor consists of a double layer capacitance the capacity of which is dependent on cell potential and represented as C(U), a nonlinear element. A packaged cell therefore consists of two carbon electrodes with a paper separator between and the assembly immersed in a conductive electrolyte. Electrical connections are made to each electrode terminal (i.e., the metal current collector foils), the remaining contact being electrolyte liquid. In the back-to-back arrangement the liquid-liquid conduction path completes the ionic pathway.

Maxwell Technologies, Inc.
Worldwide Headquarters
9244 Balboa Avenue
San Diego, CA 92123
USA
Phone: +1 858 503 3300
Fax: +1 858 503 3301

Maxwell Technologies SA
CH-1728 Rossens
Switzerland
Phone: +41 (0)26 411 85 00
Fax: +41 (0)26 411 85 05

Maxwell Technologies GmbH
Brucker Strasse 21
D-82205 Gilching
Germany
Phone: +49 (0)8105 24 16 10
Fax: +49 (0)8105 24 16 19

Maxwell Technologies, Inc. - Shanghai Representative Office
Rm.2104, Suncome Liauw's Plaza
738 Shang Cheng Road
Pudong New Area
Shanghai 200120, P.R. China
Phone: +86 21 5836 5733
Fax: +86 21 5836 5620

info@maxwell.com – www.maxwell.com

Fig. 1 Ultracapacitor Electronic Equivalent Representation

Lithium-ion electrochemical cells are modeled as a nonlinear potential source, E(SOC,T,t) that accounts for the cell capacity, Q_r amount of charge, or Ah for convenience and RC network elements. These RC elements model the internal resistance, ESR, of the lithium-ion chemistry and account for electronic and ionic contributions. At the most elementary level the lithium-ion cell is modeled as a single time constant RC network but with the resistive elements broken into two parts. A component Ri(SOC,T) models ionic concentration gradients at the electrode-electrolyte interface as well as the reaction kinetics. An electronic contribution Re(SOC,T) models the bulk resistance of the electrode terminals, the current collector foils and interfaces to electrode constituents. In order to accurately model transient effects a capacitance element is modeled across the ionic resistance component. This capacitance is effectively a double layer capacitor to account for polarization effects at the electrode-electrolyte interface or solid-electrolyte interphase, SEI, and a pseudo-capacitance effect arising from diffusion limited space charge in solution at the SEI. The model element Cdl accounts for both the double layer and pseudocapacitance contributions.

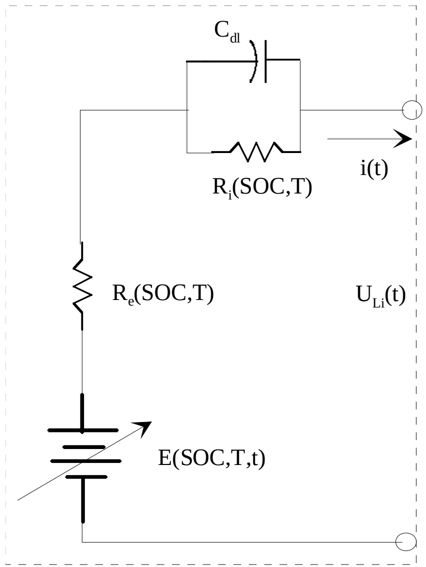


Figure 2. Lithium-ion Cell Electronic Equivalent Representation

Returning now to our main topic of ultracapacitors in combination with lithium-ion batteries one can see from the cell potential versus cell capacity traces in Figure 3 that lithium-ion has very different potential behavior than the ultracapacitor. The scales are in proper perspective to illustrate the order of magnitude energy differences between lithium-ion and ultracapacitor cells. Batteries store and deliver their energy via reduction-oxidation, redox, reactions (i.e., Faradaic or mass transfer processes) and thereby hold near constant potential until the reactant mass(s) are consumed. Ultracapacitors on the other hand are energy accumulators (i.e., non-Faradaic) and require a potential change to absorb or deliver their charge. Because of these very different voltage-current behaviors of the two energy storage components a direct parallel combination will not be as effective as a buffered configuration, what is called an active parallel combination. Active paralleling means having a dc-dc converter interface the ultracapacitor to the lithium-ion battery.

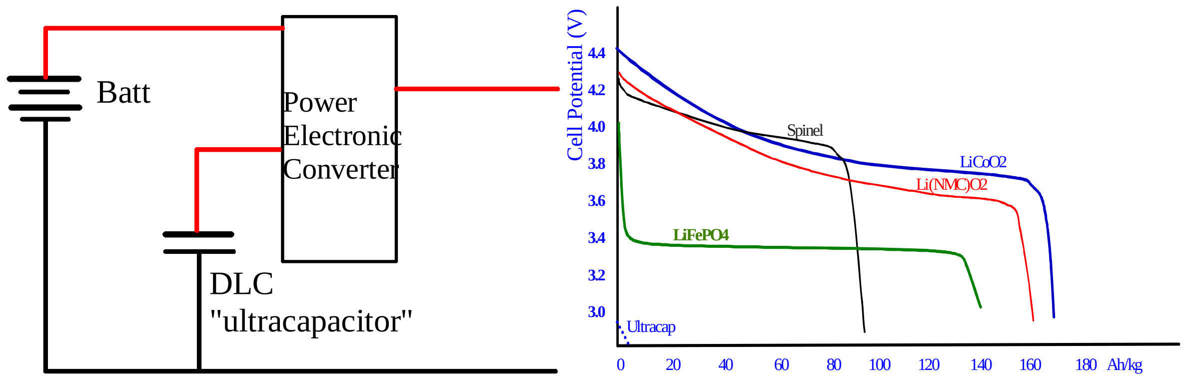


Figure 3. Active Parallel Combination of Ultracapacitor with Battery: Hybrid Energy Storage System, HESS

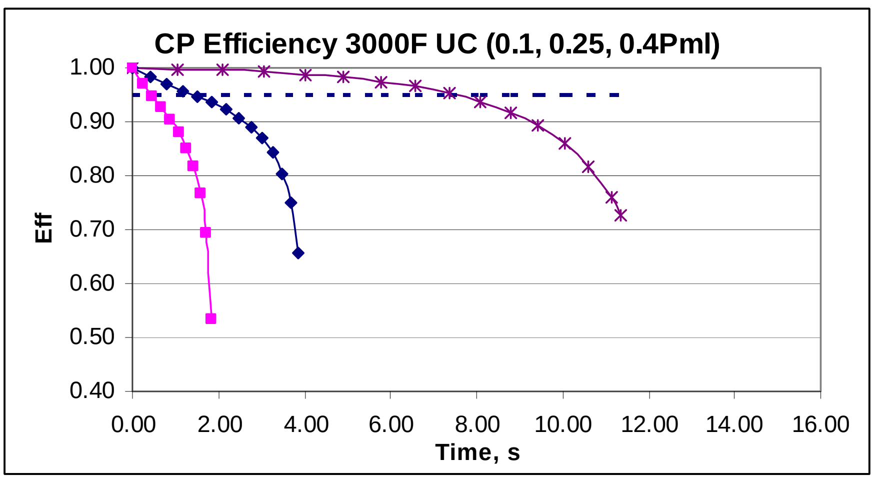
Both direct and active parallel configurations have been explored extensively over the past decade. In fact, the telecommunications industry is well aware of the benefits of the direct parallel combination of ultracapacitors with lithium cells, generally in a parallel circuit of a single lithium cell (OCV~4V) across two series connected carbon-carbon ultracapacitors (OCV=2.3 to 2.5V each). In this direct parallel example the ultracapacitor, because of its very low ESR, supplies a major portion of burst power needed during transmission while the lithium-ion cell provides all reserve power and standby power. The combination results in significant air time improvement. Similar examples can be found in bridge power for telecomm base stations where local energy storage is necessary in the event of utility line voltage sags and outages of milli-second to several seconds duration. A similar case can be made for heavy transportation, city transit buses for example, or light rail all of which are now exploring the use of ultracapacitor technology or have pilot programs underway. Figure 3 highlights the need for power electronic conversion to match an ultracapacitor pack to a lithium battery pack in order to simultaneously optimize the pulse power and energy of the combination, [1]. The demonstrated benefit of backing up a battery pack with high pulse power ultracapacitors has documented by ISE Corp. in their hybrid transit buses for municipal transit authorities.

It is necessary that the ultracapacitor plus dc-dc converter deliver a combined efficiency on the order of 90% or better to build a value proposition when combined with a lithium pack of 95% to 90% efficiency over a wide range of loading. Analysis shows that today's ultracapacitors, possessing ultra-low ESR and hence high efficiency at relatively high power levels, can indeed deliver such efficiency. Figure 4 is the result of such analysis for a typical ultracapacitor cell undergoing constant power testing. The result is 95% or better efficiency for pulse time intervals ranging from 8s at 10% of matched load power, P_{ml}, to 2s at one fourth P_{ml}, to 1s when the power loading is 40% of P_{ml}. Matched load power is defined in (1) and results when the terminal load equals the cell (or pack) internal resistance, ESR.

$$P_{ML} = \frac{U_{mx}^2}{4ESR_{dc}} \tag{1}$$

In (1) the maximum cell (pack) potential is Umx and the internal resistance is the dc value of ESR, or the ESR taken at very low (i.e., <100mHz) frequency. At such low frequency, and referring to Figures 1 and 2, the ESR will consist of Ri + Re for both ultracapacitor and lithium-ion cells.

Another observation made from Figure 4 is that the efficiency curve at constant power drops significantly as power level is increased. This is due to the fact that for a fixed power demand the ultracapacitor internal potential (i.e., the potential across the carbon-electrolyte compact layer having non-Faradaic characteristic equal to Q/C) drops non-linearly as charge Q is removed. The removed charge, Q = i(t)*t is itself nonlinear and equal to terminal power, P/Uc. Therefore, ultracapacitor current must increase as the



potential across the double layer decreases. This presents a design criterion for the interface dc-dc converter in sizing of the boost switch.

Maxwell Technologies, Inc.
Worldwide Headquarters
9244 Balboa Avenue
San Diego, CA 92123
USA
Phone: +1 858 503 3300
Fax: +1 858 503 3301

Maxwell Technologies SA
CH-1728 Rossens
Switzerland
Phone: +41 (0)26 411 85 00
Fax: +41 (0)26 411 85 05

Maxwell Technologies GmbH
Brucker Strasse 21
D-82205 Gilching
Germany
Phone: +49 (0)8105 24 16 10
Fax: +49 (0)8105 24 16 19

Maxwell Technologies, Inc. - Shanghai Representative Office
Rm.2104, Suncome Liauw's Plaza
738 Shang Cheng Road
Pudong New Area
Shanghai 200120, P.R. China
Phone: +86 21 5836 5733
Fax: +86 21 5836 5620

info@maxwell.com – www.maxwell.com

Figure 4. Ultracapacitor Constant Power Discharge Time for >95% Efficiency (8s at 0.1Pml, 2s at 0.25Pml, 1s at 0.4Pml)

The terminal potential and current behavior of the ultracapacitor during constant power loading, which can be viewed as normal operation in a vehicle traction drive, become highly nonlinear as internal potential across the carbon-electrolyte compact layer (i.e., Uco = Q/C(U)) decreases from near maximum potential. Note that in all applications that recuperate energy from the load the energy storage component must have reserve capacity to absorb the anticipated level of return energy. Figure 5 illustrates the ultracapacitor terminal voltage and current under constant power discharge at 0.1Pml and 0.4Pml.

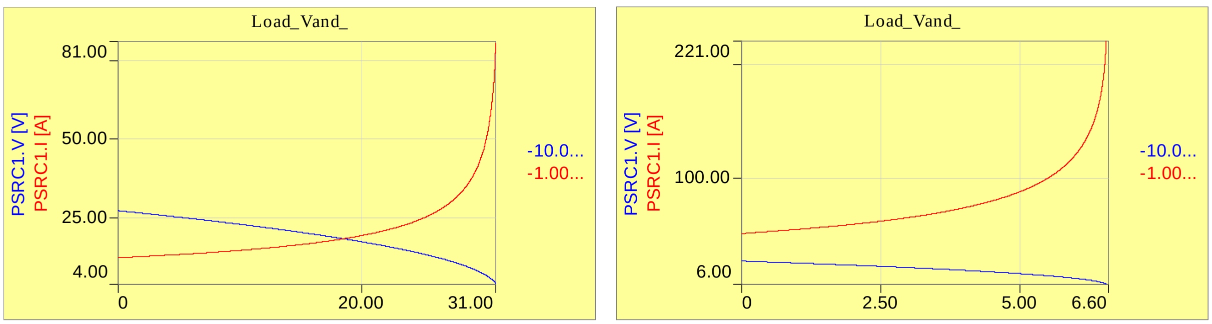


Figure 5. Ultracapacitor Discharge Characteristics Under Constant Power Loading

The nonlinear characteristics of ultracapacitor voltage and current illustrated in Figure 5 for the energy D Cell (350F, 2.5V) are taken at 10% and 40% of matched load respectively. Notice that voltage and current characteristics commence relatively linearly, trending to square law behavior and ending with a strong exponential change as potential approaches cut-off (i.e., the point at which insufficient charge remains to support the current: i(t) = dQ/dt). More details on the analytical model for constant power discharge of the ultracapacitor can be found in [2]. Table 2 summarizes the characteristics of ultracapacitor performance under constant power operation.

Table 2: Summary of powerD Cell Ultracapacitor Performance under Constant Power Discharge

Power loading	Load Watts (W)	Voltage cut-off Uco, (V)	Time to Uco (s)	Useable Energy (J)	Delivered Energy (P*t)	Energy Eff.
0.1 P_{ml} =	34	0.45	31	1260.6	1054	0.83
0.4 P_{ml} =	135	0.9	6.56	1230.5	885.6	0.72
1.0 P_{ml} =	336	1.42	1.78	1180	598.1	0.507
1.6 P_{ml} =	538	1.8	0.653	1120.6	351.3	0.313

* Total stored energy at Uc = Umx is 1295 J and for cut-off potential determined as: $U_{c0} = 2\sqrt{ESR * P_0}$

It is insightful to point out two key time constant aspects of the constant power results shown in Table 2. The power D Cell (310F, 2.5V, 2.87mΩ) characteristics result in a time constant τ = ESR*C = 0.77s. This time constant describes some very fundamental behavior of the cell and can in fact be used to define its efficiency under constant current operation. At matched load conditions the cell energy is depleted in exactly two time constants, T = 2τ = 1.78s for the power cell tested. For rapid discharge (i.e., abuse conditions) and short circuit the stored energy will be dissipated in one time constant.

Energy efficiency under high loading conditions are summarized in Table 2 and show that at matched load power levels half the stored energy is dissipated internally and half delivered to the load (i.e., efficiency is 50%). For constant power levels well below matched load conditions the ultracapacitor efficiency trends toward 100% and for cells designed for passenger vehicles the overall efficiency will be as shown in Figure 4, in the range of 95% to 98%. High efficiency means more compact modules and improved product integration, less cooling system burden so that air cooling suffices and reduced overall installation cost. Power cells packaged in modules such as the one illustrated in Figure 6 are state-of-the-art in high specific power (approaching 20kW/kg), low cost (~$12/kW) and high efficiency (>95%). Improved efficiency in energy storage means transportation systems having improved fuel economy, reduced emissions and uncompromised performance.

Figure 6 Energy D Cell Ultracapacitor Cell (350F, 2.5V, 3.2mΩ, 60g, Pml=5.6kW/kg) and Module (left), and 48V Module (right) Designed for Heavy Transportation Applications

Armed with this background on ultracapacitors and lithium-ion batteries we shift our attention now to the active parallel combination case shown as Figure 7. In this figure the Maxwell Technologies ultracapacitor model connects via a half-bridge converter (e.g., buck-boost stage consisting of line reactor L_{bb} and a phase leg module) to the lithium-ion cell model. Before describing this combination it is necessary to point out that the ultracapacitor model is a unique combination of three RC L-section filter stages listed as Ruc1Cuc1 through Ruc3Cuc3 where each L-section can be considered as representing the ionic transport mechanisms and limitations in the porous activated carbon marco, meso, and micro pores. Maxwell Technologies has released this “moment matched” transmission line model through Ansoft as a library model in Simplorer. The description is also available in Battery Design Studio software used for lithium-ion battery modeling. Referring again to Figure 7 one can see the full circuit topology that must be analyzed to even approximately model the active parallel case. The most important aspect of this configuration is the key role played by control of the dc-dc converter, in the case presented here, as one of energy management strategy, EMS, resident in a supervisory controller.

Maxwell Technologies, Inc.
Worldwide Headquarters
9244 Balboa Avenue
San Diego, CA 92123
USA
Phone: +1 858 503 3300
Fax: +1 858 503 3301

Maxwell Technologies SA
CH-1728 Rossens
Switzerland
Phone: +41 (0)26 411 85 00
Fax: +41 (0)26 411 85 05

Maxwell Technologies GmbH
Brucker Strasse 21
D-82205 Gilching
Germany
Phone: +49 (0)8105 24 16 10
Fax: +49 (0)8105 24 16 19

Maxwell Technologies, Inc. -
Shanghai Representative Office
Rm.2104, Suncome Liauw’s Plaza
738 Shang Cheng Road
Pudong New Area
Shanghai 200120, P.R. China
Phone: +86 21 5836 5733
Fax: +86 21 5836 5620

info@maxwell.com – www.maxwell.com

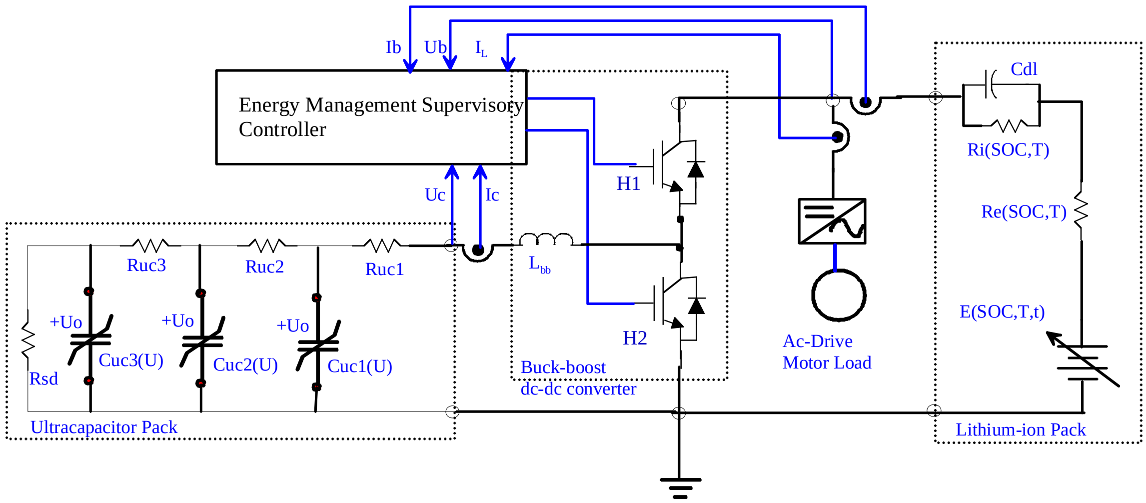


Figure 7. Ultracapacitor with dc-dc Converter plus Lithium-ion Active Parallel HESS

The EMS supervisory controller for the dc-dc interface converter has the following functions to perform:

- Continuous monitoring of load power flows, shown here as U_b and I_L sensor information
- Continuous monitoring of lithium cell (pack) power flows, shown as U_b and I_b sensor information
- Continuous monitoring of ultracapacitor cell (pack) power flows, shown here as U_c and I_c sensor information
- Generating buck-boost converter gating signals, H1 and H2, necessary to effect bi-directional power flows in proportion to accumulated SOC information on both the lithium cell (pack) and ultracapacitor cell (pack).
- Determine, based on SOC information, and connected load power demand (shown as an ac-drive electric machine load) the relative contributions of dynamic (ultracapacitor) and sustained (lithium) power levels.
- At a vehicle system level, and in cooperation with a higher level executive controller, manage the long term trend in relative SOC of the two components so that overall vehicle objectives such as fuel economy and performance can be optimized.

Before pursuing this architecture further a review of the technical literature is in order. Recent work by Miller and Auer in [3] describe an ultracapacitor pack as the dynamic energy storage component in a vehicle recuperation system that essentially opportunity charges the vehicle boardnet battery. The recuperative architecture, a variant of micro-hybridization, captures vehicle kinetic energy as a means to offset fuel consumption to power passenger amenities and vehicle accessories. There have been very recent trends in dc-dc converter developments aimed at raising efficiency into the 96% to 98% range under part to full load operation. Wang and Fahimi [4] describe a zero voltage transition, ZVT, converter that implements zero voltage switching, ZVS, for significant efficiency gains when combined with a fuel cell processor. Recall, fuel cells can be considered “soft sources” because their cell potential drops significantly with loading unlike electrochemical cells that maintain voltage rather stiffly with loading. Other investigators are evaluating architectural variants of lithium cells and ultracapacitor cells in order to minimize the component count, hence cost, of dc-dc converters. One recent example is described in the work of Guidi, Undeland and Hori [5] in which the ultracapacitor pack is segregated into an un-regulated portion and a regulated, via a dc-dc converter, portion which are then in combination with a lithium pack. Some investigators have opted for simply switching the battery and ultracapacitor branches according to loading conditions in order to circumvent the need for the dc-dc converter completely. Stienecker, Stuart and Ashtiani [6] have published and in fact, patented this concept.

Delving deeper into the literature on ultracapacitor plus battery combinations we have cases where full vehicle simulation tools are used to assess the benefits of this combination. Baisden and Emadi [7] describe in depth the use of ADVISOR[1] simulation tool the vehicle fuel economy gains obtained for different electric fractions in the propulsion components and for different ultracapacitor and lithium pack sizing. In this case, and in all related analyses the combination proves to be optimal in terms of performance and efficiency, but not necessarily in cost. Note: in Figure 5 an output ripple capacitor (preferably film type) is not shown because these components are known to be contained within the traction inverter package (shown as the ac-drive). This concern was highlighted by Schupbach and Balda [8] in their seminal work on comparing dc-dc converters for power management in hybrid electric vehicles. The result of their work however, was to highlight the fact that the half-bridge, or buck-boost, converter was most desireable for interfacing an ultracapacitor to a battery pack. In even earlier work, and again aimed at converter-less interfacing of ultracapacitors, because of cost, with batteries was done where the battery “load-leveled” the power demand while the

[1] U.S. National Renewable Energy Laboratory, Golden, CO., ADVISOR documentation: http://www.ctts.nrel.gov/analysis/

Maxwell Technologies, Inc.
Worldwide Headquarters
9244 Balboa Avenue
San Diego, CA 92123
USA
Phone: +1 858 503 3300
Fax: +1 858 503 3301

Maxwell Technologies SA
CH-1728 Rossens
Switzerland
Phone: +41 (0)26 411 85 00
Fax: +41 (0)26 411 85 05

Maxwell Technologies GmbH
Brucker Strasse 21
D-82205 Gilching
Germany
Phone: +49 (0)8105 24 16 10
Fax: +49 (0)8105 24 16 19

Maxwell Technologies, Inc. - Shanghai Representative Office
Rm.2104, Suncome Liauw's Plaza
738 Shang Cheng Road
Pudong New Area
Shanghai 200120, P.R. China
Phone: +86 21 5836 5733
Fax: +86 21 5836 5620

info@maxwell.com – www.maxwell.com

ultracapacitor provided dynamic power. Miller [9] took the initiative on this combination following the U.S. program Partnership for a New Generation of Vehicles, PNGV, that had a goal of an 80 mpg (i.e., 1liter/100km) "supercar". This is the precursor of today's direct parallel combination of hybrid energy storage system.

In conclusion:
The system shown in Figure 7 remains at the forefront of power electronics research to address the remaining technology gaps in meeting vehicle level requirements for energy storage over the full operating temperature range and without any sacrifice in performance. Lithium alone cannot meet this challenge because it will lose a significant portion of its power capability for temperatures below -10^{o}C. Nor can ultracapacitors acting alone meet the energy requirements of passenger vehicles without exceeding allowable package space. What is recommended is the active paralleling of ultracapacitors with lithium, but with power flows subject to supervisory energy management strategies that seek to maintain both the energy component within its high efficient range – meaning low power stress levels, and the pulse power component within its energy range – meaning without incurring wide SOC swings that shave off efficiency points. The active parallel combination thus requires the most efficient power processor, a bi-directional dc-dc converter, that is comfortable with wide voltage variation on the input and admits instantaneous power reversals without loss of regulation. This article introduces the reader to state-of-art energy storage technologies and the requirements of dc-dc converter to take advantage of energy rich lithium-ion and power dense ultracapacitors. Every investigator over the past decade who has pursued ultracapacitor plus battery combination agree that in combination the benefits far outweigh the performance of either component acting alone. But much remains to build a value proposition and this will only be accomplished with further advances in power electronics for dc-dc conversion.

Reference:

[1] Maxwell Technologies: http://www.maxwell.com/ultracapacitors/battery_power/p21_case.asp

[2] John M. Miller, "Ultracapacitor Efficiency under Constant Power Conditions: Prospects for Lithium Battery plus Ultracapacitor Hybrid Energy Storage Systems," 3rd International Symposium on Large Ultracapacitor Technology and Application, UCAP, Advanced Automotive Battery Conference, AABC 2007, Long Beach, CA., 17 May 2007

[3] John M. Miller, Juergen Auer, "Ultracapacitors, the Boost for Hybrid Vehicles", Asia Pacific Automotive Engineering Conference, Track 1: Power Train Technology Hybrid and Electric Power Systems, 5-8 August 2007, Hollywood, CA, USA

[4] Shiju Wang, Babak Fahimi, "High Efficiency and Compact dc/dc Converter for High Power Fuel Cell Systems," IEEE power electronics society magazine feature article, Vol. 19, Nr. 3, July 2007

[5] Giuseppe Guidi, Tore M. Undeland, Yoichi Hori, "An Interface Converter with Reduced VA Ratings for Battery-Supercapacitor Mixed Systems, IEEE Power Conversion Conference, PCC2007, Nagoya, Japan, 2-5 April, 2007

[6] Adam W. Stienecker, Thomas Stuart, Cyrus Ashtiani, "A Combined Ultracapacitor-Lead Acid Battery Energy Storage System for Mild Hybrid Electric Vehicles, IEEE Vehicle Power and Propulsion Conference, VPP 2005, Paris, FR, 7-9 Sept 2005

[7] Andrew C. Basiden, Ali Emadi, "ADVISOR-Based Model of Battery and an Ultra-Capacitor Energy Source for Hybrid Electric Vehicles," IEEE Transactions on Vehicular Technology, Vol. 53, Nr. 1, Jan. 2004

[8] Roberto M. Schupbach, Juan C. Balda, "Comparing dc-dc Converters for Power Management in Hybrid Electric Vehicles," IEEE International Electric Machines and Drives Conference, MonaTerrace Hotel, Madison, WI, 1-4 June 2003

[9] John R. Miller, "Capacitor/Battery Load-Leveling of Hybrid Vehicles without use of Active Interface Electronics," Sixth International Seminar on Double Layer Capacitors and Similar Energy Storage Devices," Deerfield Beach, Florida, 9-11 Dec. 1996