WHITE PAPER

POWER MODULES ENABLE ELECTRIC DRIVE SYSTEMS

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Introduction

Automotive electrical system architecture development and product planning has been underway for several years as the automotive industry prepares for the largest systemic change in decades: the transition from heat engine propulsion to electric drive; 12 volts to 42 volts; and distributed electrical power. A variety of options exist, driven by technology and economics, and opinions continue to change as to how and when the transition will occur. Current conventional wisdom says that the migration to hybrids, 12 to 42 volts, and distributed power will occur in stages. The migration appears to be taking longer than originally anticipated, and is likely to be a continuous evolution over the next decade or longer.

The modern automobile is becoming ever more sophisticated, evolving towards an intelligent electrically powered platform. Consumers no longer use cars solely for transportation. They expect greater comfort, convenience, entertainment, and safety than ever before. At the same time great pressure is being exerted both politically and by the consumer to have less dependence on fossil fuel and greater reduction in pollution and greenhouse gasses. Automotive companies are appealing to this expectation by putting more and more creature comforts into our vehicles, a trend that has resulted in significant loads on the electrical system, while at the same time developing various strategies for reducing fuel consumption and pollutants. An effective means to accommodate these increased demands is by migrating to a higher voltage system. The implications of this migration have an interesting feedback behavior; more power-hungry peripheral components on the vehicle create the need for a more powerful electrical system. Conversely, availability of more electrical power can accommodate the long-term requirement to achieve better performance and efficiency by taking advantage of the increased electrical power to drive motors, actuators, and control boxes which currently are mechanically or hydraulically driven. Ultimately, all subsystems must be electrically powered if we are to achieve all-electric vehicles such as fuel cell or battery powered automobiles.

Numerous automotive firms are well into the production design cycle for ultracapacitor-based power-trains and subsystems, as they recognize the advantages and availability of the ultracapacitor to meet their business and technical requirements. Ultracapacitors are becoming a standard energy storage option. Ultracapacitors are globally available, cost-effective, perform well in automotive systems, and are considered a peer to any other option for commercial energy storage requirements.

This paper will explore some of the application concepts utilizing drive-train and distributed power concepts to satisfy the two converging demands of environment and consumer.

Ability

Ultracapacitors are being designed into a myriad of vehicle systems today. They are outstanding power components, with characteristics that allow designers significant system flexibility. They can deliver and accept full current at any state of charge with high efficiency and long life. They can be continuously cycled at high rate. Ultracapacitors maintain their ability to perform in very cold environments (-40C). They are simple to control; state-of-charge is a straightforward voltage measurement, and state-of-health can be quickly calculated with a brief dynamic measurement. Since they have no inherent fixed voltage, they can be operated over a wide voltage range, and can be completely discharged to zero volts. Long cycle life (measured in hundreds of thousands of cycles) allows the ultracapacitor to last the life of the vehicle. In those applications where life-cycle cost is of high value (e.g. embedded power modules, hybrid buses, trucks), using ultracapacitors can significantly reduce the overall cost of operating the vehicle. Systems designers can take advantage of these various characteristics to optimize the performance and life of the entire system.

Ultracapacitors are best suited to perform in those applications that require short bursts of power, interspersed with longer durations of low power requirements. Engineers continue to learn how to design systems that use two different components to achieve an optimal solution for both power and energy. One model is that of a cache of power; the ultracapacitor is sized for maximum peak power, while the primary energy storage is a large device sized for maximum continuous power (Figure 1). The primary energy storage can be a fuel engine, high-energy batteries, or a fuel cell. System designers size the ultracapacitor for the difference between maximum continuous and maximum peak power, to take full advantage of both components.

Powertrains

Integrating ultracapacitors with other energy devices solves many challenges that are not feasibly solved using a single energy storage device. One example is Continental ISAD's integration of high-energy lead-acid batteries and ultracapacitors [1]. By combining these two technologies, Continental has created a system that has the excellent energy, self-discharge, availability, and low cost associated with lead-acid technology, and the high charge acceptance, high-efficiency, cycle stability, and excellent low-temperature performance of the ultracapacitor. To illustrate how the two technologies complement each other, Continental presented a spider chart, which overlaid the relative metrics of each component (Figure 2). The total system performance is depicted by the added System line, which represents the system solution (conservatively averaging the value of the two components).

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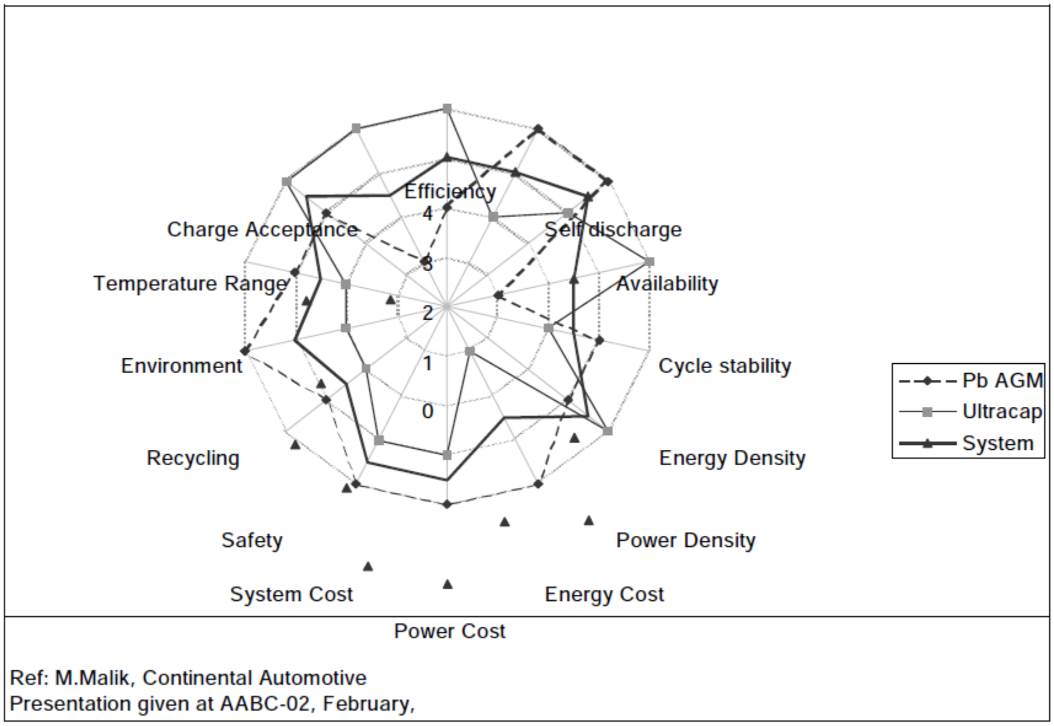

Figure 2: System Analysis with Ultracapacitors and Pb-AGM batteries.

Another example of an integrated system is Siemens VDO's ISG system [2]. Siemens' solution also integrates lead-acid batteries and ultracapacitors as the energy storage solution. They demonstrated that both the acceleration and regenerative braking performance was superior to lead-acid alone, increasing acceleration boost from 4kW to up to 10kW, and increasing regenerative braking from 1kW to up to 10kW. Siemens exploited the high current capability of the ultracapacitor by using it exclusively for engine starting via the ISG, and found that in the case where the 42V energy storage subsystem was discharged, the ultracapacitor could be charged via the 14V system (via a DC/DC converter already in the system), allowing the engine to be started in case of emergency.

These two examples are representative of the approach to migrating from 12 to 42 volts. Both designs take advantage of the power of ultracapacitors to conserve energy by allowing the engine to stop while the automobile is not moving and then to be restarted nearly instantly on tip in of the throttle. The design also allows regenerative braking energy to be captured thereby significantly increasing efficiency and reducing pollution.

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The use of engine start/stop and regenerative braking has been estimated to produce between 7 and 15% increased fuel efficiency while reducing pollution by an even greater percentage.

Various other announced programs are integrating ultracapacitors into vehicle power-trains.

- MAN bus, in cooperation with Siemens Transportation Systems, Voith Turbo Antriebstechnik, and EPCOS (licensed manufacturer of Maxwell Technologies ultracapacitor), has developed a diesel-electric city bus with an ultracapacitor-based regenerative braking system [3].

- VW, in collaboration with Maxwell Technologies Montena division, the Swiss Federal Institute of Technology in Zurich, and the Paul Scherrer Institute and other partners, integrated ultracapacitors into a hybrid fuel cell vehicle [4]. The VW BORA vehicle successfully crossed the Simplon pass on January 16, 2002, and was presented at the Geneva Motor Show in March, 2002.

- Honda has been developing ultracapacitor-based vehicles for years. In 1997, Honda announced the development of their Integrated Motor Assist (IMA) unit, which included an ultracapacitor system [5]. More recently, Honda announced the FCX-V3, a fuel-cell vehicle equipped with an ultracapacitor for improved response and performance [6].

- Nissan has introduced a commercially available hybrid electric diesel truck in Japan which features a “super power capacitor” for regenerative braking and launch assist [7].

- Toyota announced the ES3 concept vehicle in September 2001, which integrates an ultracapacitor-based braking system [8].

- Electric Fuel Corporation (EFC) recently announced its all-electric, zinc-air fuel cell bus has demonstrated a range of 127 miles in rigorous urban conditions. The company attributed the record-breaking range to the addition of a pack of (Maxwell Technologies) ultracapacitors, which extended the bus' range by 25 percent [9].

- Oshkosh Truck developed the first heavy-payload defense truck with a hybrid electric drive. The HEMTT-LHS tactical defense truck employs a diesel-fueled drive that is suitable to commercial as well as military vehicles, and consists of a 400kW generator coupled with Maxwell Technologies ultracapacitors. “Ultracapacitors,” says Oshkosh, “last up to 10 times longer, operate in wider temperature ranges and function more efficiently” than batteries. “They are capable of receiving high levels of regenerated energy for highly responsive braking as well” [10].

These vehicles run the gamut from concept to production-intent. In addition to the announced programs listed here, numerous other development programs utilizing ultracapacitors for hybrid trucks, buses, and passenger vehicles are underway. These programs are all focused on the ultracapacitor as part of the electrical energy storage required for the power-train.

Migration From 12 to 24 Volts

Many papers, studies, and conferences have described the transition from 12 to 42 volts. It has become obvious during the development phase of the 12- to 42-volt transition that 42 volts is not a "big bang" phenomenon. The 42V transition will be evolutionary, occurring in several steps. Each step will be used to phase in new elements of the final architecture. Table 2 is a high level summary of how this evolution could occur.

	Now	Stage II	Stage III	Stage IV	Stage V
Architecture*	12V	12/42V	42/12V	42/12V	42V
Alternator Voltage	12V	12V	42V	42V	42V
Charging	12V-Alternator	12V-Alternator 42V-DC/DC	42V-Alternator 12V- DC/DC	42V-ISG Regen 12V- DC/DC	42V-ISG Regen
42V Function	SLI	Intermittent Loads	Ring-gear Starting	Creep/Crawl	Light Hybrid
Power Rating	1.5 kW	2.5 kW	4 – 6 kW	6-12 kW	6-18 kW
Peak Current**	110A	220A	150A	300A	450A

* The current convention in architecture nomenclature is that the alternator voltage determines the description, e.g. Stage II is 12/42 because the alternator operates at 12 volts.

** Peak current can exceed 600A for several tenths of a second during engine start, which is important to note, but the peak current here is for sustained maximum load.

Regardless of how the 42V system evolves, the use of dual voltages and the growing list of features and efficiencies required on new vehicles makes it difficult to produce a cost-effective, reliable electrical distribution system based on today's model of a centralized architecture. The significant industry attention to 42-volt systems creates many opportunities for improved efficiency and enhanced features that are enabled by having a distributed power capability.

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With the evolution of the voltage from 12 to 42 and the design of integrated starter alternators, additional functions are possible if power modules are part of the design concept. In particular the use of torque assist and regenerative braking allows a majority of the benefits of hybrid vehicles without the high cost and complexity of a complete power-train replacement. A local energy storage unit, committed solely to the power-train functions of engine starting, torque assist, and regenerative braking, reduces the size and length of high-power cabling that would be necessary if one used a single, central energy storage unit. The advantages of using power modules and energy modules as a system become readily apparent. As in all the other distributed power applications, the traction power module must have very high cycle life, high current capability for both charge acceptance (braking) and discharge (acceleration/starting), high current at low voltage and low temperature, and low maintenance.

Fuel Cell – Ultracapacitor Hybrids

There are several types of fuel cells being considered for automobiles. The most common type is the hydrogen-oxygen fuel cell, known as the Proton Exchange Membrane or PEM fuel cell. The key advantage of this type of fuel cell is that it uses hydrogen for fuel and oxygen from the atmosphere to create electricity and its waste output is warm moist air.

These fuel cells are efficient and dynamic enough for automobile use with a few drawbacks. There is no existing infrastructure for hydrogen delivery, hydrogen is not easy to handle safely, and the tanks are rather large in volume and must be very strong to withstand the very high pressures of storage and potential accidents. Even though the fuel cell is capable of being dynamic enough to handle transients, it is large and costly if sized to meet the maximum load. Therefore, it is more cost-effective to have a hybrid design with a fuel cell and a bank of ultracapacitors. The ultracapacitors are capable of handling very dynamic loads such as initial acceleration and have the added benefit of absorbing braking energy.

An alternative to the hydrogen fuel design is to have a system called a reformer, which would break down more readily available fuels such as gasoline or methanol to generate hydrogen as a by product.

The reformer is a preprocessor to the fuel cell and requires warm-up time and high electrical power to initiate. It then produces hydrogen and CO2, where the hydrogen is fed to the fuel cell. This added need for start power is an excellent application for ultracapacitors. This power-up mode requires several seconds of high power to both start the reformer and begin to augment the powertrain drive for initial operation of the vehicle.

The metal-fueled fuel cells, such as zinc-air, would use ultracapacitors for the same reasons as the hydrogen-based fuel cells. The difference would be related to the sizing of the power boost, which depends on the dynamic response of the fuel cell system. Two examples of successful fuel cell and ultracapacitor systems are the VW fuel cell demonstration [4], and the recently announced NYC bus using a zinc-air fuel cell and ultracapacitors [9].

Distributed Power Concepts

The modern automobile has become more and more dependent on electrical subsystems as features proliferate. Computer control modules, active suspension, powered/heated/air-conditioned seating, navigation systems, and audio-video entertainment systems individually and collectively place huge loads on the power system of the vehicle. As these loads switch on and off, the implications on quality electrical power have not been realized. Current architectures are weak in handling multiple large transient loads such as these. The availability and reliability of electrical power for robust operation, as well as during failure modes and accidents, needs to be incorporated into the design of future power systems.

Conceptually, the modern automobile is becoming a computer-based processing system. The industrial world has addressed their computer-based processing systems by developing robust and redundant power quality solutions. Automobiles will need to be designed using a similar philosophy. The use of redundant power supplies and fail-soft computer-based systems will increase in importance as future generations of automobiles become more dependent on silicon-based operation.

Distributed power is an architecture that can be used to make systems more robust, while at the same time reduce the cost, weight, and complexity of the power net. Centralized power control requires that a separate wire be run from the central control box (which contains fuses, relays, and switches) to the device being powered. Each wire must carry the full current of the load, and must be routed through the vehicle, sometimes over long, tortuous routes.

In a distributed architecture, power is generated in one location, and is distributed via a limited number of common power buses. Control signals are also distributed over a limited number of common communications buses. Power and signal are delivered to a local distribution node, which incorporates intelligent electronic controls, and possibly energy storage. The local processor controls local use of power without the need to run multiple wires long distances to each specific point-of-use. Where local power is used intermittently, energy storage of the local power node can provide that power, while the vehicle's power bus need only supply the average power. This use of a local power buffer significantly reduces the size of the main power bus wire. The use of a limited number of common power buses throughout the vehicle significantly reduces the total number of wires being routed throughout the vehicle. By reducing the size of individual wires, the length of high-current-carrying wires, and the total number of wires in the vehicle, the system becomes less complex, more robust and reliable, and since the cost of processors continue to decrease faster than that of copper wire, ultimately the power system costs less.

Applications Leveraging Distributed Power

1. Remote Power

Many mechanically or hydraulically powered subsystems can be converted to electric power; particularly those that are used intermittently. When mechanically driven, these loads draw power continuously, whether or not they are being used, resulting in parasitic losses. When electrically driven, these loads only draw power when actually used, effectively eliminating parasitic losses. The most common of these loads is power steering.

Most of the time, power steering is quiescent, drawing little power for actual steering. When called upon, the power requirement is a brief, high power pulse of less than one to two seconds. The profile for a typical electrically powered steering event is a one- to three-second ramp to approximately 2000 watts for several hundred milliseconds, which quickly returns to quiescent. In a centralized power architecture, the power required can be supplied by the central energy storage, but this would require a very heavy and costly power cable. The voltage drop due to the high current could require that either the cable or the energy storage system be oversized. Several system advantages are realized with a distributed power module that contains energy storage. The module can be sized for the application and can be located near the point of use, eliminating the need to run a long, high-power cable. The main power bus need only supply average current, so it can also be reduced in size. In case of failure of the main power bus, there is reserve energy for emergency. The key challenges to implementing this solution are the fact that this is a new architecture, and that any energy storage has significant requirements for long life, and little or no maintenance.

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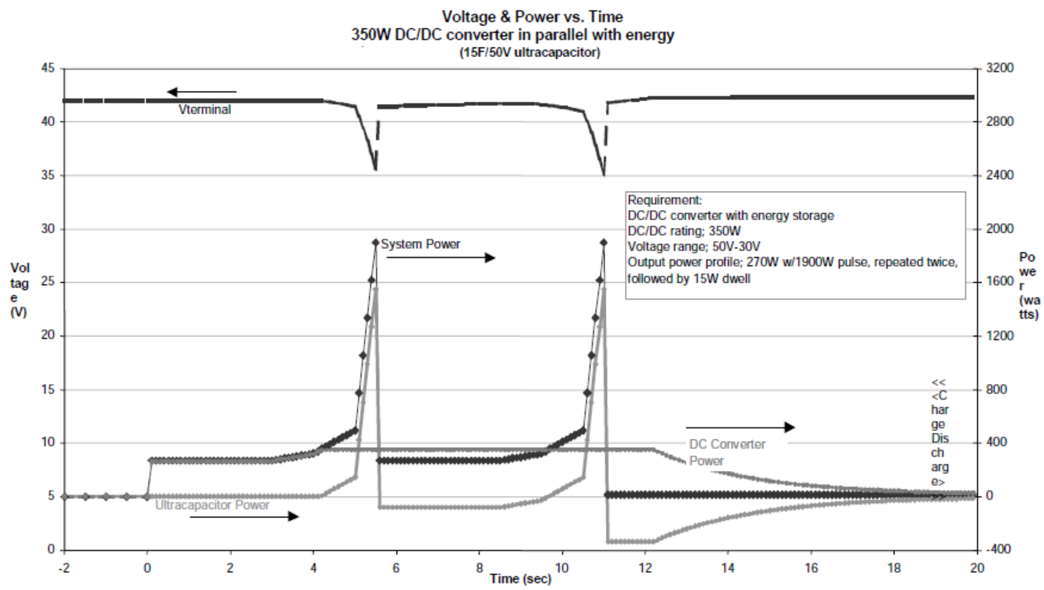

Figure 3: Power Steering Profile

Figure 3 is an analysis of a typical power steering event. This system includes a 350W converter supplying 42V from the 12V bus, and an energy storage device (in this case, an ultracapacitor) load-leveling the power steering event. Without the use of energy storage, the converter would have to be sized to supply the 2000W peak, and be able to respond quickly to this transient demand.

2. Backup Power

The use of silicon-based controllers has become significant and continues to grow dramatically. These systems offer long life, high reliability, high flexibility, continuously adaptive optimization and increased functionality all at low cost. The dependency on these systems is so great that certain critical functions cannot be allowed to fail hard for safety reasons. As the new power net architecture develops it is important to take into account this added requirement for high availability. This requirement can be in conflict with other safety features such as positive disconnect of the energy storage during a high-impact accident.

Integrating local energy storage is a proven strategy for hardening controllers. It is prudent to design a backup power source into the electronic box, which allows soft fail and a safer shutdown. Requirements of the local energy storage include no maintenance, long life, high reliability, and operation over a wide temperature range. This backup concept is very common in industrial and commercial computer based systems.

3. Power Actuation

Mechanical latches for doors, trunks and hoods could be activated by solenoid. Some of the current automobiles are already using door and trunk solenoids. Future cars may be built with electrical solenoids without mechanical backup. This is most likely in the full-featured modern door, which has an airbag, power windows, speakers, and safety bars. The requirement for local power is driven mostly by the lack of space for a mechanical connection from the handle to the latch. Having the power module in the door eliminates the heavy cabling associated with a centralized energy storage architecture, and provides an added safety function. In case of a severe accident where the centralized energy storage unit is either destroyed or disconnected, the door can still be opened. This requires an energy storage unit with long life, high cycle life, excellent cold weather operation, no maintenance, and small size.

Energy Storage Characteristics for Power Modules

Selecting an energy storage technology for integration within distributed power modules requires an understanding of the performance characteristics of each technology. Table 2 compares current energy storage technologies for power storage modules. The values are numerical from 1 to 5 where 1 is good and 5 is poor. The criteria are not for SLI applications but for distributed power considerations.

Desirable characteristic	Pb-Acid	Li+	NiMH	Ultracapacitor
Life of the application	4	3	2	1
Low maintenance	3	2	2	1
Wide temperature range	2	3	4	1
Cost-effective	1	4	3	2
High current in & out	4	3	3	1
High cycle life	4	3	1	1
Embedded in system	5	3	4	1
Sized for the requirement	2	1	1	1
Size and Weight	3	2	3	2
Safety	2	2	3	2

Table 2: Energy Storage Characteristics

- **Life of the application** refers to the ability of the energy storage technology to last the life of the application, i.e. the life of the vehicle; requiring life performance of 6-10 years, and 100,000's of cycles.

- **Low maintenance** refers to the need for little, if any, explicit maintenance service on the vehicle, and also the ability to accurately monitor the condition of the energy storage unit.

- **Wide temperature range** refers to performance at low temperature, and life and safety at high temperature.

- **Cost-effective** refers to market price solely; it does not consider life cycle costs, which can be significant, and yet difficult to define consistently.

- **High current in & out** refers to the ability to accept energy at high rates, as well as deliver energy at high rates, and at various states of charge.

- **High cycle life** refers to the systems' cycle, rather than to an idealized low-rate, full-capacity (or partial-capacity) cycle.

- **Embedded in system** refers to the ability to integrate the energy storage technology with the associated control circuitry directly into a distributed power module, rather than having it as a separate, or centralized, energy storage unit.

- **Sized for the application** refers to the ability to tailor the size and configuration of the energy storage unit to most closely fit the form, fit, and function of the specific distributed energy storage requirement.

- **Size and weight** and **Safety** are self-explanatory.

Why ultracapacitors?

In distributed power applications, ultracapacitors offer advantages over other energy storage devices. Their long-life, high power capability, durable design, wide temperature range, and low maintenance all lend to the optimization of the solution. Cost and availability were the primary reasons that ultracapacitors were not used in automobiles in the past. These issues are now addressed. Availability has increased because of the demand for ultracapacitors in the electronics and industrial markets, and production centers now exist in Asia, Europe, and the United States. Global suppliers such as Maxwell Technologies and Panasonic are also aggressively addressing the cost issue. Global source of supply, low-cost, high-volume, durable design, and dual sourcing are all prerequisites for suppliers to the automotive industry. Ultracapacitors are an excellent choice, and may be the most appropriate selection, for distributed power systems in automobiles.

Global Availability

Ultracapacitors are available now in quantity from a variety of international firms. The challenge for ultracapacitor manufacturers has been to demonstrate not only outstanding performance (which can be accomplished with laboratory and prototype parts), but also demonstrate volume production capability with sustained high quality. Customers require a reliable source of components when they make the commitment to go into production. The success of their own designs will rest in part on a reliable source of ultracapacitors.

Ultracapacitor manufacturers have made considerable investments to break the cycle of supply and demand. Historically, the demand for ultracapacitors in the automotive industry has been relatively low to nonexistent. From the perspective of the automotive manufacturers, production managers focused on the availability of component supply, purchasing managers demanded low prices, and engineers were learning how ultracapacitors behave and perform. Without factories in place, supply was inconsistent, prices were high, and few ultracapacitors were available for the design engineers to use in prototypes. Ultracapacitor manufacturers, on the other hand, were hard-pressed to make significant investment decisions when the demand was so low; how much could one invest up front in a factory based on anticipated, but as yet unrealized, markets? A factory would be producing at a fraction of its capacity for some time, feeding the multi-year design cycles with low-volume product for design and evaluation, often for years before ever seeing a high-volume production order which could begin to pay back the investment. The risk of program delays or cancellations in the automotive industry is not insignificant.

To break this chicken or egg cycle, companies in Asia, the United States, and Europe have made significant capital investments and are in production today. Factories are producing ultracapacitors in a variety of sizes for a multitude of applications. Systems designers can now integrate ultracapacitor cells into their specific applications. Larger ultracapacitor products, integrated from individual cells, are available from suppliers, which are suitable for 12V and 42V applications. Third-party suppliers are currently offering ultracapacitor sub-systems ranging from 12V to hundreds of volts.

Production volumes vary by model, with smaller cells available in higher volume due to the significantly higher demand, particularly in the consumer electronics market with its faster design cycles. For example, one factory is currently running at mass production volumes, operating a partial shift on a line capable of greater than one-and-a-half million parts per month. These smaller cells are currently used in consumer electronics, small industrial electrical systems, and have been designed into automotive electrical sub-systems, which are currently being marketed by Tier 1 suppliers. Larger cells, designed for automotive power-trains and large industrial systems, are in the early stages of three-to-five year design cycles. Volume production capability in the thousands per month is available now, more than adequate to meet the demand of this long design cycle. Factories are being expanded ahead of demand, and production capabilities of hundreds of thousands per month are planned for 2003, well ahead of any anticipated large production orders.

The availability of ultracapacitors is no longer a constraint on the automotive industry’s ability to evaluate ultracapacitors and design them into the next generation of advanced vehicles for powertrains and electrical subsystems. With a demonstrated production capability and consistent supply, the concern of the production manager is addressed. The purchasing manager now has their say; is the technology affordable?

Affordability

Ultracapacitors are affordable when designed into high-volume applications. By affordable, we mean that the price fits the customers' requirements, while the costs to manufacture the ultracapacitor are sufficiently low that a reasonable margin remains for the ultracapacitor manufacturer to have a sustainable business. Price is based on the cost model of the customers' application. The customer (e.g. the automobile manufacturer) must be able to purchase their components at a price that allows them to assemble the vehicle, and then sell that vehicle at a price that is acceptable to the end consumer, while maintaining an acceptable margin of profitability. An interesting metric is that the average automobile is priced at $7-$10 per pound. Obviously, many components are significantly more expensive than this, but in the aggregate the automobile must average out around this price to the end consumer.

Ultracapacitor cost is based on materials, factory and capital costs. The challenge for ultracapacitor manufacturers is to drive their costs down to the point where the total manufacturing costs are below the price requirements of the customer to allow sufficient margin. This has been accomplished by developing designs which use lower-cost materials, by efficient manufacturing processes, effective design and use of factories, and by producing a sufficient volume to amortize the factory and capital costs over a large enough production volume.

Today, ultracapacitor prices are less than $0.03 per farad (the price of a 2700F cell is less than $60 in 10k piece volumes), and will be available at prices approaching $0.01 per farad by 2004 (less than $30 per 2700F cell in 1 million piece volume). This compares with $0.10 per farad two years ago, and $1 per farad six years ago. This is a two order of magnitude reduction in price in six years; a tremendous accomplishment.

One note of interest when comparing ultracapacitor prices to other energy storage options; one must be sure to use equivalent metrics, appropriate for the application. A common figure of merit is cost per energy, expressed in $/Wh. When using this figure of merit, one must be sure to consider the actual energy used in the application. One may find an advanced battery that has the potential to deliver 50-100Wh per kg, at a low discharge rate. In the actual application, one may only use the advanced battery within a 10% state-of-charge range, at a high discharge rate. This is a common usage in some hybrid power-train architectures. In this application, the advanced battery may only deliver 5-10Wh per kg. This example effectively increases the cost in terms of $/Wh by a factor of 10. When comparing costs of various technologies, one must ensure that the actual costs associated with the application are considered, rather than generic performance metrics, which may not be appropriate to the specific application.

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Summary

Ultracapacitors are available here and now as a peer to batteries and fuel cells when considered as an option for balancing energy and power in systems. Ultracapacitors, batteries, and fuel cells each have their own unique characteristics that, individually, may not meet the designer's specific requirements, but may do so in combination. Systems are being designed and fielded today using ultracapacitors in combination with other energy storage systems which meet the performance and cost targets for production vehicles within the next automotive design cycle. Ultracapacitors are available from multiple sources around the globe. The price of ultracapacitors has come down by orders of magnitude, and is now within the range of pennies per farad. Production-intent electrical systems are being developed with ultracapacitors as key enabling components for a variety of new architectures. The technology has emerged from its infancy and is now successfully meeting the technical and business requirements of the automotive industry for advanced electrical systems.

Today's advanced electrical systems include more high power loads than ever before. Wiring harnesses are getting more complex, and often represent a significant warranty cost. Dual voltage systems (12V/42V) introduce new architectures that require multiple energy storage devices for different voltage requirements. One strategy for solving the challenges of dual-voltage and high power loads is distributing power modules throughout the vehicle. The use of multiple energy storage elements buried throughout the vehicle demands that the energy storage technology selected must have long life, low maintenance, flexibility of sizing, wide temperature range, in addition to excellent performance. Ultracapacitors are a premier technology being designed in today as a fundamental element in distributing power throughout the vehicle, increasing reliability and improving performance, while simplifying numerous aspects of design.

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