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Energy storage and management systems for 42 V architectures

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Abstract

Vehicle manufacturers worldwide have recognized the trend toward increased on-board power demands is causing a need to raise the electrical system voltage from the present standard of 12 V to a higher, yet safe, voltage. One of the major challenges emerging from the transition to higher voltages is the size, weight, volume, cost and complexity of the energy storage system required to support the vehicle system and its loads. This paper discusses these changes, their implications, and presents potential solutions to address the future needs of vehicle manufacturers. © 2001 Elsevier Science B.V. All rights reserved.

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1. Overview

The last major change in the vehicle electrical system voltage occurred more than 40 years ago when the universal standard was raised from 6 to 12 V. Since then, the vehicle electrical system has developed from a simple series of electromechanical devices to an extremely complex array of electrical and electronic components, all of which require electrical energy to operate. When the vehicle's engine is running, the alternator is designed to supply the bulk of the electrical requirements. However, the role of the battery has gradually been expanded from the traditional starting, lighting, ignition (SLI) function to include load leveling and standby power functions. The total electrical load demand in North American vehicles of varying feature content as a function of model year is shown in Fig. 1 [1].

Reacting to the constant demand for additional feature content as well as emission reductions, fuel economy, and safety, vehicle designers worldwide have concluded the time is right for another step-function change in vehicle electrical system voltage. Rather than doubling the system voltage to 24 V, the consensus among vehicle developers is to elevate the voltage to the maximum safe level, while maintaining an 'open' electrical system. This results in a system voltage of 42 V and a battery voltage of 36 V [2].

While the higher voltage electrical system will present opportunities for reducing size and weight of components, thereby enhancing fuel economy and/or CAFE ratings, it also will permit engineers to completely redesign the vehicle electrical and electronic system architecture. Power sapping, belt driven loads such as air conditioners, water pumps and power steering will become electrical appliances operated only on demand. Advanced electronic technologies such as steer-by-wire, brake-by-wire and mobile office, only a dream with the 12 V electrical system, will become realities with the high voltage system. In addition, emissions-lowering, electrically heated catalytic converters and automatic engine stop at idle for fuel economy and emission control will become much more feasible with elevated system voltage. Not all components on a vehicle demonstrate enhanced efficiency at elevated voltages. Light bulbs and computers, in particular, actually prefer lower voltages and, as a result, multiple voltages are likely to optimize the performance of the entire system.

A systems approach is vital to the successful conversion to the high voltage vehicle. Existing as well as new components must be carefully optimized to gain the maximum advantage of the change. Many of the current components must be completely redesigned and optimized as a part of the new system. One such component is the 12 V, lead–acid storage battery.

The lead–acid battery has been in existence for over 100 years and the 14 V vehicle electrical system architecture has been a standard for more than 40 years. The electrical performance and life of 12 V automotive batteries has been significantly improved over the past 50 years. The result is a modern, cost-effective product capable of delivering both power and energy. However, a direct extrapolation of this technology to 42 V would result in an unacceptable bulky, heavy, expensive and compromised device with limited

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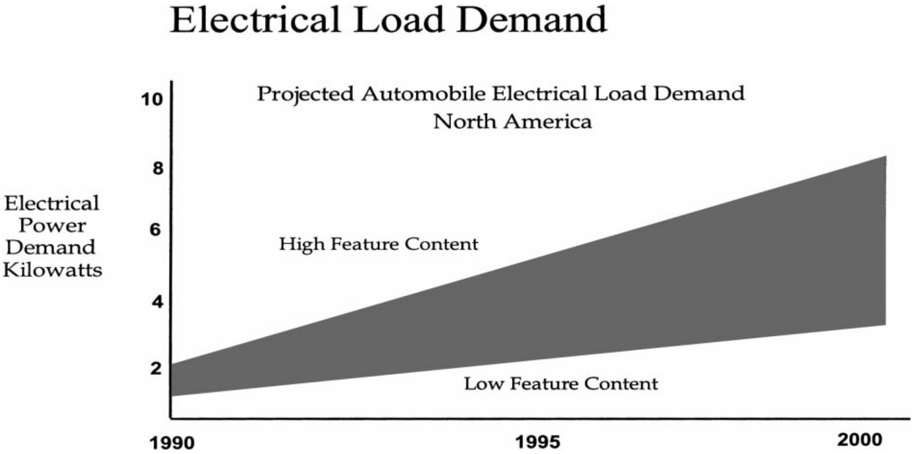

Fig. 1. Vehicle electrical power demand trend.

capability in such important characteristics as rapid rechargeability (charge acceptance) and packaging flexibility.

2. Applications

To properly specify the battery as part of the energy storage and management system, the design engineer must understand the performance and life needs of the product. Traditional 14 V systems have power requirements up to 2 kW. In this application the lead acid battery with present alternators is the best choice of value.

Future 42 V vehicle applications can be divided into three major groupings. The first of these is the 14/42 V Standard Alternator. The present alternator design is incapable of delivering power much over 2 kW. Although, some new designs of alternators have been developed to improve the efficiency and output, their cost and the resulting heavy wires for power distribution may not be advantageous. This has brought about the concept of a system that runs-off of a 42 V alternator and 36 V battery, which reduces losses in the alternator diodes and decreases I^2R losses in the wires due to the reduced current. These systems will need either a dc/dc converter or a second tap-off the alternator to supply the 12 V loads that are not changed over to 42 V. It is believed that over time most loads will migrate to 42 V. These systems will most likely handle power up to 4 kW.

The next grouping is the 14/42 V integrated starter/alternator (ISA, CSA or KSG). The need for increased fuel efficiency and reduced emissions can be addressed in part with improvements in the efficiency of the electrical system. One embodiment of this is in ISA systems. Present alternator systems range from 40 to 65% efficiency, depending on design, temperature and motor speed. The new ISA systems are 75–85% efficient. On a vehicle with loads of 4 kW, a 20% gain in efficiency equates to about 2–3 miles per gallon or 0.8–1.3 km/l. With these savings and the ability to deliver some boost energy, systems of 3–8 kW will mostly likely be designed and should be able to support the higher cost. The battery system for this application still can be an advanced lead–acid battery as long as stop/start strategies are not employed.

The final grouping is the 14/42 V ISA (ISA, CSA or KSG) with stop/start and regenerative braking. If stop/start and regenerative braking become part of the application, then a deep-cycle battery system should be specified. The battery must have both good energy and power capability over the entire range of operating state-of-charge (SOC) and operating temperature. Continuous operation in a partial SOC, to capture regenerative energy, will likely preclude the use of the lead–acid battery at this time. Nickel metal hydride or lithium-ion technology may be better suited. System power requirements will expand to 4–15 kW to handle the extra load demand for stop/start. The above-mentioned 14/42 V ISA system also has been often referred to as a ‘‘mild hybrid’’ system, that is, it only uses the Starter/Alternator intermittently.

3. Battery systems

Increasing load demands and duty cycle soon will outstrip the capabilities of the present 12 V lead–acid battery. Practical considerations require optimization of power, energy, and life while not exceeding customer requirements for weight and volume. Current flooded, lead–acid systems will not be capable of fulfilling the need for the battery to cycle. Furthermore, changes in application, such as operating at partial SOC, may require the use of alternate chemistries such as nickel metal hydride or lithium-ion as seen in hybrid electric vehicles.

Lead–acid technologies currently available include flat-plate flooded and valve regulated designs such as flat plate and spiral wound absorptive glass mat (AGM). As the new vehicle architectures shift the duty cycle away from shallow discharging to deeper depths of discharge, AGM designs will hold the advantage over flooded batteries. Additional drivers in favor of AGM include performance, weight and

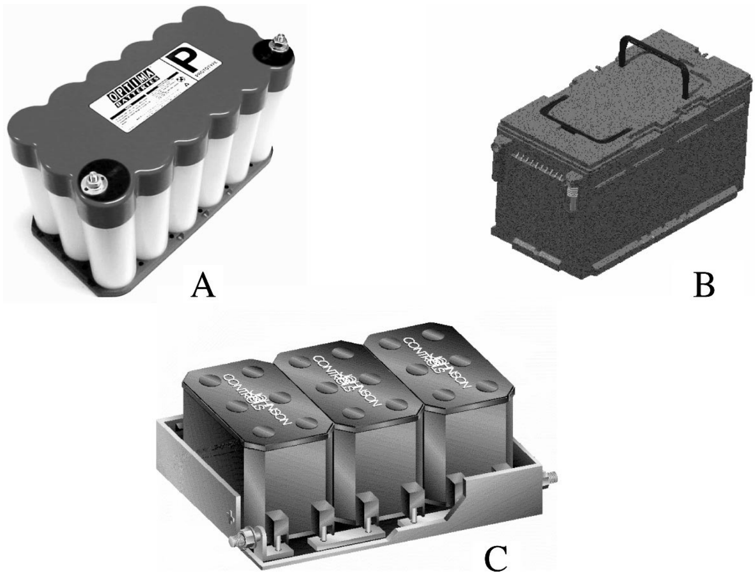

Fig. 2. Examples of 42 V batteries.

packaging flexibility. AGM designs demonstrate good high rate capability, and afford minimal gassing through the gas recombination cycle. The use of compressed, glass mat separators in the AGM construction imparts excellent vibration resistance and improved cycle life when compared to flooded designs. In addition, the AGM battery offers packaging flexibility in that it may be oriented and placed in locations not possible with flooded designs.

Fig. 2 shows three examples of projected 42 V designs. The Optima battery, labeled A, consists of 18 spiral wound cells in an H8 footprint. The flat plate battery, labeled B is an H8 footprint with pin terminations. It contains 18 cells in a monobloc container that can be either flooded or AGM by design. Battery C consists of three Johnson Controls' Inspira® batteries connected in series. All three designs are fitted with resealable valves for gas pressure relief and can incorporate anti-flash back protection.

Performance simulations for these designs are shown in Table 1. Several factors went into the designs used to simulate the electrical performance. First, 4 kW of power was targeted at -30°C for 10 s of continuous discharge to a 27 V cut-off. Second, material was balanced to give at least 25 A h in capacity at the C/5 discharge rate. It must be emphasized, the data is for comparison purposes only.

Material properties for the AGM separator dictate a certain minimum thickness must be used for compatibility with automated assembly equipment. Thicker, higher basis weight, separator material must be used in automated assembly of flat plate AGM designs when compared to spiral wound constructions. Spiral designs bring plates of opposing polarity closer together and thereby minimize IR losses resulting in better high rate performance. The performance simulations in Table 1 reflect this both for Optima and Inspira designs when compared to the flat plate AGM. Inspira goes one step further in that it incorporates very thin lead foil electrodes with very thin separators. This combination provides excellent high rate power characteristics.

Currently, the Inspira product is made in three different sizes with the largest having a capacity rating of 6.0 A h at C/5. While the obstacles to scaling up to a 25 A h size are substantial at this time, the 6.0 A h Inspira design has sufficient power to function as a 36 V starting battery in dual battery systems. However, if a single battery must supply both energy and power, the designer must choose one of the other three options. Spiral wound AGM offers superior cycling performance and a leak proof, low gassing system versus flooded lead–acid. Compared to traditional flat plate AGM, the spiral design yields a capability to design for higher power requirements.

Table 1
Performance simulations for battery systems

	C/5 capacity (A h)	Power at -30°C/10 s to 27 V (kW s)	CCA at -17.8°C to 7.2 V	Weight (kg)
Flat plate flooded	29.3	4.9	475	32.4
Flat plate AGM	27.2	4.2	440	27.1
Optima	28.7	5.0	500	28.2
Inspira	26.3	15.1	775	30.3

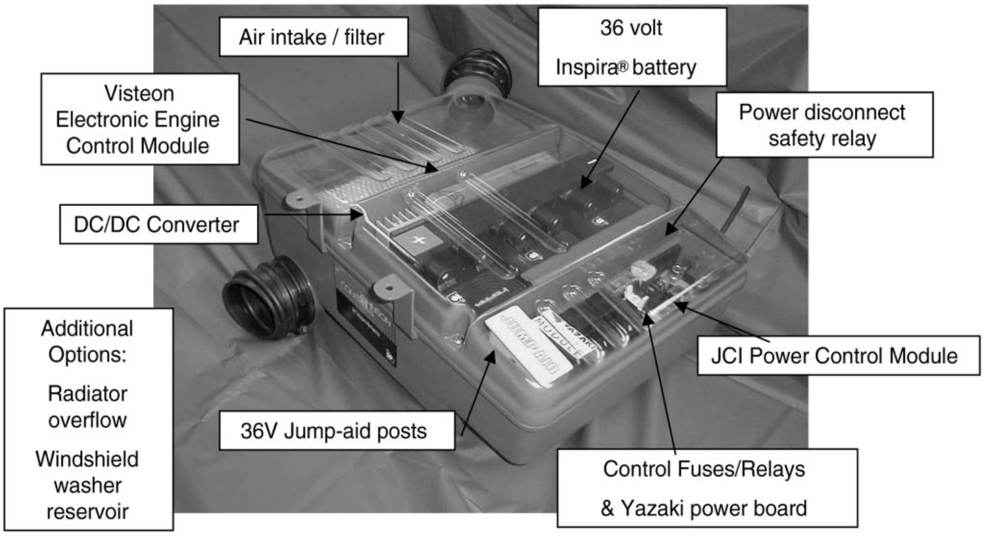

Fig. 3. Advanced power system (APS).

4. Systems integration and battery management

Batteries often are purchased as a commodity by the automotive industry based on their capacity, size and cold crank ratings alone. There has been little work to integrate the battery or energy system as an active module on the vehicle communication network.

Future vehicle architectures may likely contain multiple batteries as well as different battery chemistries. There is an enormous potential for improving the performance and life of the overall energy storage system. An energy management system (EMS) will be required to manage and leverage the performance of multiple batteries. An EMS can contain inputs and controllers that can manage the vehicle loads and the charging parameters to reach an optimum balance between system performance and battery life. There are additional opportunities to improve start protection by having continuous feedback to the vehicle control system on the relative SOC and the state-of-health (SOH) of the battery.

An EMS also will be required to enable fuel saving drive strategies such as stop/start and regenerative braking. The stop/start strategy shuts the engine off during stationary idling conditions. stop/start strategies require communication of deliverable power. Regenerative braking allows a portion of the vehicle's kinetic energy to be put back into the energy system on board. Regenerative braking requires communication of recharge capability. These functions need to be transparent and seamless to the driver. Also, these functions are only employed when the energy system is in a condition to support them. The role of the EMS is to

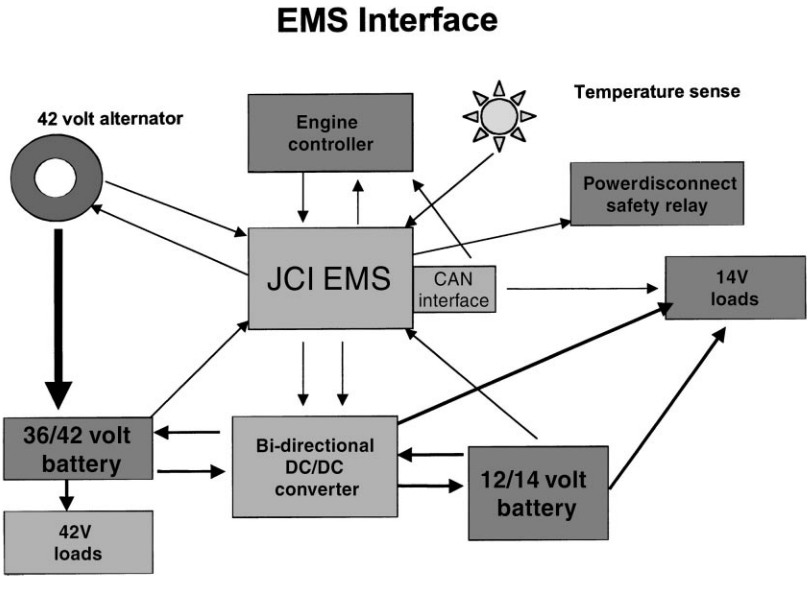

Fig. 4. EMS interface with vehicle electrical system.

communicate, upon request from the vehicle system, the available power or recharge capability based upon the relative SOC and the SOH of the various batteries. The relative SOC takes into account the rate at which the power is to be delivered as well as the SOH of the battery.

An energy system in future vehicles can logically contain much more hardware than just batteries. Hardware such as dc/dc converters, fuses and electronics can be integrated into the energy system as a module.

An example of an integrated energy system is the Johnson Controls Advanced Power System (APS) shown in Fig. 3. The packaging of the energy system is combined with a number of components that allow for reduced space, lower weight and increased reliability. Reduction in parts, engineering and assembly are also benefits to the vehicle manufacturer.

The system incorporates the air intake manifold, the 36 V battery and fusing system to combine three separate plastic tray components into one. Along with these components the dc/dc converter, Jump Aid Posts and Johnson Controls' EMS controller are packaged together to deliver a pre-tested system that increases component life and helps improve gas mileage. Fig. 4 shows a schematic depicting the EMS interface with the vehicle electrical system. Communication takes place between the EMS and the individual components that comprise the electrical system. This includes the energy storage devices, dc/dc converters, all loads, the alternator and the engine controller.

Johnson Controls presently has a system that incorporates an EMS, dc/dc converter, 12 and 36 V battery system in a Jeep Grand Cherokee that will be shown at the Convergence 2000 show. The impact of this system on fuel economy will be quantified in rigorous testing this fall and winter.

5. Conclusions

Over the next few years, new vehicle electrical system architectures will emerge that will require 42 V battery power. Of the different lead–acid technologies, the spiral wound AGM design (Optima) offers excellent overall life and performance in this application. More advanced battery systems and different chemistries capable of withstanding operation at a partial SOC will be required for vehicle systems using stop/start and regenerative braking strategies.

It also will be important to manage the energy demands of the vehicle. This can be done either with an EMS controller or software that can be embedded in the Engine Computer.

Energy system integration, as seen in the APS example, can help offset the new system costs and allow for improved product performance and life. To accomplish these objectives we must start now in defining the application of the batteries and determining how to package, size and manage the energy that the product will see during its expected life.

Acknowledgements

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