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42-V battery requirements from an automaker's perspective

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Abstract

Present and future automotive electrical loads are surveyed relative to power and electrochemical storage requirements. It is concluded that existing power and energy needs are near the maximum capability of the existing 14-V system, and that future automotive loads may be 10 kW or more. The efficiency of the electrical distribution system at this power level requires a higher voltage and safety considerations dictate that a 42-V limit will be the most satisfactory standard. The higher-voltage systems will likely include advanced controls, thermal management, and more complex architectures. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Efficiency; Electrical distribution system; Battery controls and diagnostics; Future automotive power; 42 V

1. Introduction

Since Kettering's development of the electric ignition system for automobiles in 1911 [1], the requirement for electrical energy-storage has increased progressively until the present time. Moreover, it shows no sign of abating, particularly since a significant portion (if not an outright majority) of options offered as new customer-oriented features in vehicles are electrical in nature. This paper reviews the current state of electrical automotive features, describes the parameters required for selection of the battery system, and then outlines the rationale for a higher voltage system.

2. Automotive electrical loads

The electrical load requirements for the modern automobile range from milliwatt parasitic loads that maintain on-board computers to tens of kilowatt traction power loads used to drive large vehicles for 100 km or more. These loads have diverse characteristics that lead to specialized battery requirements for each. In total, however, these loads must be supported by a single electrical generation and storage system.

There are literally hundreds of electrical loads on present day automobile, and many more are being contemplated in the quest for products that satisfy (or create) consumer needs. Many of these loads are mature and well developed, while others have only recently reached the marketplace or are still under development. The loads can be roughly classified into engine and propulsion, driveability and regulatory, or convenience and comfort. These classifications are described in the paragraphs below.

2.1. Engine and propulsion requirements

Engine and propulsion loads are those used for engine start and motive power. These loads are typically in the kilowatt range and may be applied for a few hundred milliseconds (as for engine crank) or for hours (as for electric drive). These can be divided into crank loads, hybrid drive loads, and electric drive loads. The functions of each of these loads are described schematically in Fig. 1 and in the text below.

Crank is generally described as the power needed to overcome the friction, compression, and inertia of the engine to increase the crankshaft rotation speed sufficiently to fire the cylinders. The crank power will vary from engine to engine and with temperature, but is usually in the kilowatt range.

Hybrid vehicle architecture allows a relatively small battery to augment the internal combustion power supplied to a drivetrain. The battery also often allows the vehicle to recoup a portion of its kinetic energy as electrical power during a braking event. In addition, most hybrid operating strategies provide non-idling (stop/start) performance, where accessory loads are maintained for at least several tens of seconds. Variants of hybrid vehicles use these functions to various degrees: soft hybrids are vehicles that provide the

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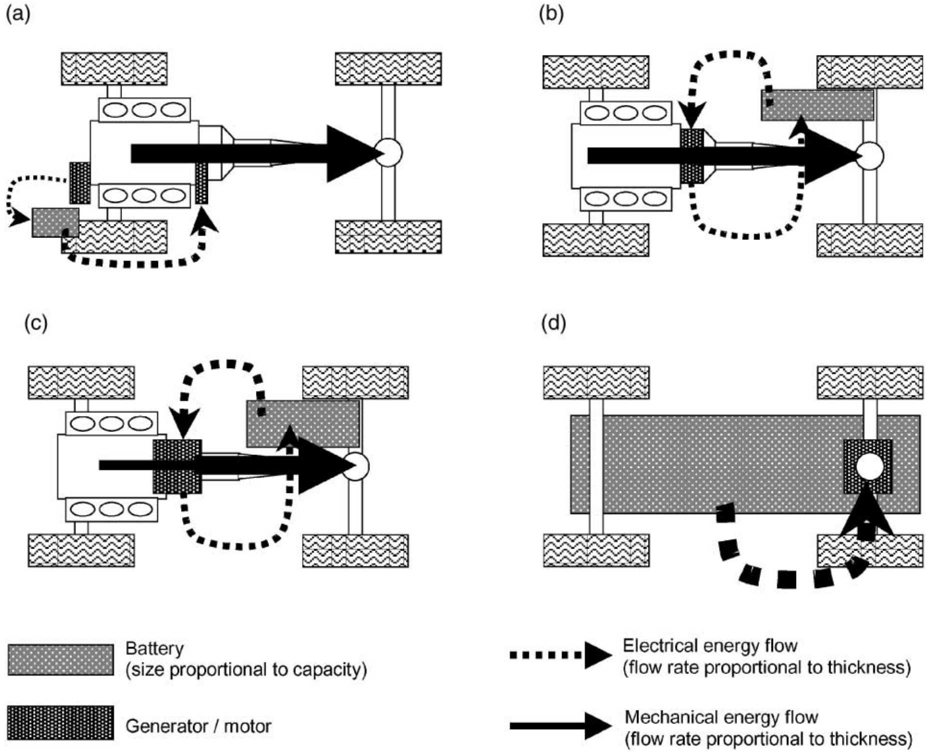

Fig. 1. Automotive electric systems: (a) automotive (SLI); (b) soft hybrid; (c) full hybrid; (d) electric drive.

basic function of start/stop and regenerative braking with some boost; a full hybrid provides start/stop, regenerative braking, and more substantial boost that may propel the vehicle at least short distances without the need for power from the internal combustion engine (ICE).

Electric drive (EV) refers to systems that use only stored electrochemical energy for propulsion. These vehicles will vary in size from golf-cart sized neighborhood vehicles to full-sized trucks. EV power requirements will range up to that provided by an ICE. Table 1 provides budget estimates of the power, time, and engine and propulsion loads, and correlates these to occurrence within vehicle types.

2.2. *Driveability and regulatory requirements*

The driveability and regulatory group loads include those that contribute to smooth engine function, handling, basic climate control, and compliance with corporate and government regulations. The loads vary from milliamps for control components on standby to kilowatts for braking, valve actuation and emissions control.

Within this group, it is necessary to quantify the duty cycles. Some devices with very high loads may in fact only demand the energy intermittently and then only for brief periods, whereas other devices with low loads may demand power continuously and may thus become a principal requirement in the electrical distribution system. For example, Fig. 2 presents the duration of stop events recorded for a mixture of North American vehicles, drives and environments. These data may be used with the known key-on stop requirements to determine a utilization factor that can be applied to equations for the sizing of energy storage (in terms of energy, life, or power). The plots in Fig. 2 also show how perturbations to this curve can be used to estimate the effects of specific drive schedules such as those used in public service vehicles.

2.3. *Convenience and comfort requirements*

Convenience and comfort group loads include those that provide additional features that are optional to the propulsion function of the automobile. Nevertheless, these devices are often key marketing devices that must be supported. As in the two previous categories, the values given in Table 1 are only typical; actual values will depend on the device design and application.

2.4. *Total loads*

The situation shown by relevant selections from Table 1 exemplifies the substantial electrical demands on many vehicles today (approximately 2 kW peak). Generator capacity is usually sufficient for all but the most demanding duty cycles (Fig. 3), and so power and energy contributions from the battery are relatively modest. If, however, any of the newer innovations for comfort, driveability, or propulsion enhancement are adopted, it is clear that both generator capacity and storage capacity must be upgraded proportionally to

Table 1
Selected device power, occurrence, and vehicle type[a]

Electrical feature	Status	Power			Occurrence					Vehicle type			
		Minimum power (W)	Maximum power (W)	Average usage (%)	Cold start (0.3–6 s)	Drive (30 s–3 h)	Key-on stop (0–20 s)	Hot start (0.5 s)	Key-off (1 min–30 day)	ICE	Soft hybrid	Full hybrid	EV
Engine propulsion													
Crank	Mature	2000	8000	100	✓			✓		✓	✓	✓	
Boost	Developmental	3000	10000	50		✓					✓	✓	
Hybrid propulsion	Existing	10000	60000	50		✓						✓	
Propulsion	Existing	10000	90000	100		✓							✓
Driveability/regulatory													
Electric all-wheel steering	Developmental	+++	++++	30		✓				✓	✓	✓	✓
Electronic valve activation	Developmental	2000	4000	10	✓	✓	✓	✓		✓	✓	✓	
Electric power steering	Developmental	+++	++++	25		✓				✓	✓	✓	✓
Brake by wire	Developmental	+++	++++	20		✓				✓	✓	✓	✓
Advanced powertrain control	Developmental	+++	++++	25		✓				✓	✓	✓	✓
Active suspension	Existing	+++	++++	25		✓				✓	✓	✓	✓
Anti-lock braking	Mature	1000	3000	1		✓				✓	✓	✓	✓
Electronic fuel injection	Existing	+++	++++	100	✓	✓	✓	✓		✓	✓	✓	
Traction control	Developmental	+++	++++	25		✓				✓	✓	✓	✓
Electrically heated catalytic converter	Developmental	500	2000	100	✓					✓	✓	✓	
Electronic distributorless ignition	Developmental	++	+++	100	✓	✓	✓	✓		✓	✓	✓	
Electric powered water pump	Developmental	300	500	100		✓				✓	✓	✓	✓
Ignition and fueling	Mature	++	+++	100	✓	✓	✓	✓		✓	✓	✓	
Heated screens	Developmental	600	1500	25		✓				✓	✓	✓	✓
Electronic fuel injection	Mature	++	++	30	✓	✓	✓	✓		✓	✓	✓	
HVAC fans	Mature	30	300	100		✓	✓	✓		✓	✓	✓	✓
Main beam	Mature	120	180	10		✓	✓	✓		✓	✓	✓	✓
Fog front	Mature	80	140	2		✓	✓	✓		✓	✓	✓	✓
Dipped beam	Mature	100	130	20		✓	✓	✓		✓	✓	✓	✓
Brakes	Mature	20	100	40		✓				✓	✓	✓	✓
Electronic controls modules	Mature	10	10	100	✓	✓	✓	✓	✓		✓	✓	✓
Fog rear	Mature	40	70	2		✓	✓	✓		✓	✓	✓	✓
Windshield wipers	Mature	50	100	5		✓	✓	✓		✓	✓	✓	✓
Side lights	Mature	30	60	25		✓	✓	✓		✓	✓	✓	✓
Heater water pump	Mature	50	50	25		✓	✓	✓		✓	✓	✓	✓
Heated mirrors	Mature	20	30	50		✓	✓	✓		✓	✓	✓	✓
Electronic controls modules (off-key)	Mature	0.1	0.5	100					✓	✓	✓	✓	✓
System and component diagnostics	Existing	+	+	100	✓	✓	✓	✓	✓	✓	✓	✓	✓
Collision avoidance	Developmental	+	+	100		✓				✓	✓	✓	✓
Blind-spot sensors	Developmental	+	+	100		✓				✓	✓	✓	✓

Table 1 (*Continued*)

Electrical feature	Status	Power			Occurrence					Vehicle type			
		Minimum power (W)	Maximum power (W)	Average usage (%)	Cold start (0.3–6 s)	Drive (30 s–3 h)	Key-on stop (0–20 s)	Hot start (0.5 s)	Key-off (1 min–30 day)	ICE	Soft hybrid	Full hybrid	EV
Comfort/convenience													
Supplemental instant heat	Developmental	2000	3000	25		✓	✓			✓	✓	✓	✓
Zone adjustable climate control	Developmental	1000	2000	25		✓	✓			✓	✓	✓	✓
Electric powered air conditioning	Developmental	1000	2000	25		✓	✓			✓	✓	✓	✓
Electric power point/appliances	Developmental	500	2000	20		✓	✓	✓	✓	✓	✓	✓	✓
Heated seats	Existing	100	300	5		✓	✓	✓		✓	✓	✓	✓
Memory seats	Mature	20	150	1					✓	✓	✓	✓	✓
CD	Mature	5	100	10		✓	✓	✓		✓	✓	✓	✓
Phone	Mature	1	20	10		✓	✓	✓		✓	✓	✓	✓
Electrochromic glass	Developmental	5	50	50		✓	✓	✓		✓	✓	✓	✓
Navigation aids	Developmental	+	+	25		✓	✓	✓		✓	✓	✓	✓

[a] All values are approximate and are for estimation purposes only.

the power and energy requirements of the given device. These estimates are consistent with historical trends; if the growth realized during the previous two decades of powertrain electronics continues at 6% per year then, by 2020, the electrical generation capacity in passenger vehicles will approach 10 kW in vehicles without electric propulsion and nearly 30 kW in vehicles with electric drive for propulsion [2].

Although it is beyond the scope of this discussion to consider generator technology in any detail, the arguments above show that, in order to discuss battery needs, consideration should be given to at least a few of the innovations and strategies planned for power generation. These are as follows.

2.4.1. Enhanced power-generators/alternators

Future designs are expected to provide at least 2 kW.

2.4.2. Integrated starter–generator

This device, in either direct or belt-drive configuration, is expected to provide a maximum of 6–12 kW of charge power, although 2–3 kW will probably be the optimum charge rate based on likely operating strategies.

2.4.3. Hybrid/electric-drive regenerative braking

The regenerative power will depend on the system and motor size. Up to 60 kW may be available for short periods (5–20 s) and could be used to augment loads. Even with improved electrical generation capacity, the battery will be called upon to play a larger role in automotive peak-shaving. As such, the battery will be greatly affected by any of the new devices that come to market.

3. Standing requirements for energy storage

Although there have been many propositions for improved energy storage, any new technology will also have to meet other standing requirements before they may be considered as a solution. It is essential to meet minimum performance levels in factors such as safety, recycleability, manufacturability, commonality, ease of service, reliability, temperature operating range, and weight. Then, given that performance to these specifications is sufficient, cost must be carefully managed to provide the optimum technical solution. Some of the key requirements relevant to energy storage are described below.

3.1. Safety

Battery safety consists of resistance to overcharge, overdischarge, accidental physical damage, short-circuit behavior, and fire exposure. Short-period overcharge and overdischarge is a near inevitable situation given the highly dynamic power requirements present on most automotive electrical distribution systems.

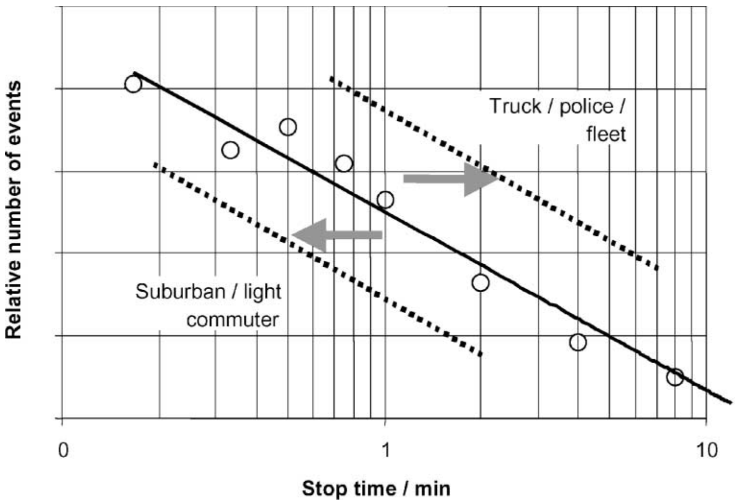

Fig. 2. Typical time and frequency of idle events in North American cars and light trucks.

Some physical damage to the battery must also be anticipated, particularly in crash scenarios. Short-circuit behavior must be managed since a high rate of self-reaction may lead to thermal runaway. Fire exposure tends to be more of an issue with advanced non-aqueous batteries, as high temperature often leads to electrolyte ejection and sometimes ignition.

3.2. Environmental

Any vehicle component produced for today's market must address environmental concerns such as emissions, recycleability, and potential toxic contamination. Emissions to consider are both gaseous and liquid. By tradition, hydrogen emissions from aqueous batteries that could lead to explosive air mixtures have been an accepted risk which can be mitigated by free movement of air around the battery. Nevertheless, this attribute cannot be taken for granted in future batteries, particularly if the batteries are of large capacity, are assumed to accept charge at a high rate, or are packaged in either a restricted space or in the passenger compartment. Liquid emissions have been handled through local drainage. Again, this strategy cannot be assumed for the future, particularly for non-aqueous chemistries.

Risk of environmental contamination is particularly significant for batteries. Such risk is intimately connected to the recycleability properties of the battery and the recycling infrastructure since un-reclaimed batteries are likely to be disposed of in landfills. For this reason, chemistries that include highly toxic elements (such as cadmium) are unlikely to gain wide commercial acceptance in North America in automotive applications.

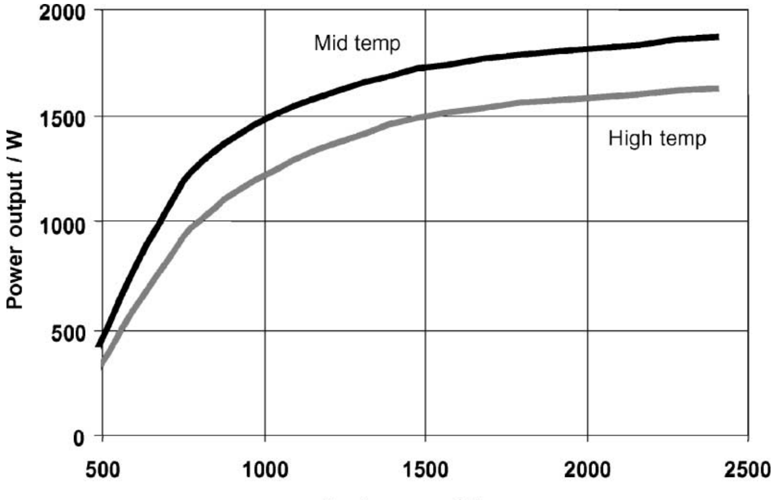

Fig. 3. Typical generator output.

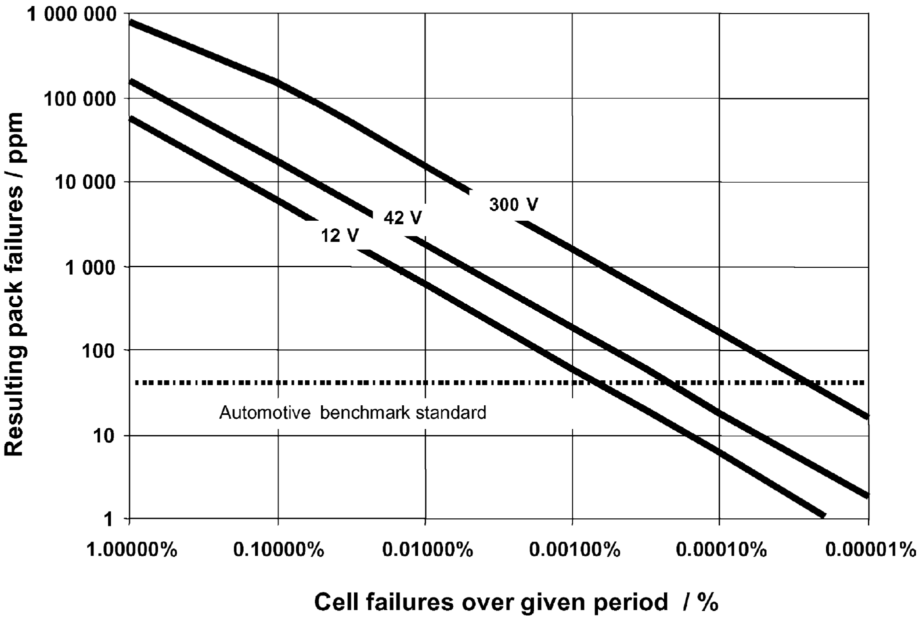

Fig. 4. Relation between cell reliability and battery failure rate.

3.3. Reliability

Within the last few decades, the automobile industry has undergone a revolution in overall vehicle reliability. Given the large number of components and potential failure modes, to satisfy customer expectations a component must provide six-sigma (99.9999%) reliability over its operational life [3]. This life is now assumed to be 10 years or 250 km. Present automotive (SLI) batteries do not perform to this standard, of course, but it is expected that pressure will come to bear on the industry to perform to this level in years to come. While a lead-acid battery with a 10-year life is not likely to be produced within the near future, a 5–7-year battery will probably be an industry stipulation soon.

The most challenging application for batteries lies in high-voltage series strings of cells, where open-circuit failures can result in sudden failure of the system. Calculations based on the theory of system-life distribution show that to achieve an automotive standard of 12 ppm failures, a six-cell lead-acid battery would require 99.999% cell reliability. By contrast, an 18-cell battery will require 99.9997% cell reliability to achieve the same failure rate (Fig. 4).

3.4. Weight savings

A common metric in vehicle design is the cost of weight reduction. This value spans all components and provides a benchmark for decision-making. If a vehicle program has a weight-reduction target, it generally will consider a number of actions to reduce mass. An example of this is the use of high-strength/low-density alloys for vehicle components, where the cost for this action may be on the order of US$ 15 per kg; the proposed advanced battery design must provide the same weight-reduction benefit for this cost (or less) in order to be considered as a replacement technology on a weight-reduction basis.

3.5. Cost

The automobile industry is decidedly competitive with a highly elastic consumer demand, and pricing is a marketing tool that can determine in large part the success or failure of a vehicle line. Replacements for existing technologies must therefore either demonstrate superior technology that is marketable to the consumer, so the incremental cost can be recovered, or the cost of the replacement technology must be less than the original technology. It is also important to note that all aspects of cost must be considered and include any required advanced controls, packaging, thermal management, or additional costs to vehicle infrastructure.

4. Automotive voltages

4.1. Voltage relation to power efficiency

The effect of high energy demands on the overall efficiency relative to the present 14-V/2-kW electrical distribution system is shown in Fig. 5. At a total average load of 6 kW, the efficiencies of the electrical distribution system fall to less than 65%, and at 17 kW, the efficiency will be less than 40%. The impact of this inefficiency on the corporate average fuel economy will be significant, namely, ~0.4 L per 100 km for every kilowatt lost.

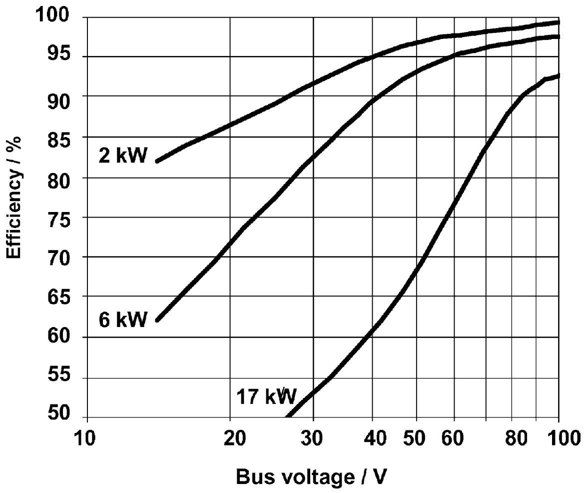

Fig. 5. Dependence of electrical distribution efficiency on voltage [4].

4.2. High voltage selection

Before 1950, 6 V was the standard in most automotive applications, but by 1960 nearly all automobiles had adopted the 14-V standard. These changes were driven by better ignition performance, faster cranking speed for high compression engines, and a higher alternator output, which had then reached 500 W [5]. Analogously, it can be expected that future higher power requirements beyond the present 2 kW threshold will logically lead to a higher voltage system for reasons of efficiency.

High-voltage systems (those in excess of 60 V) will provide better efficiency, but it is equally necessary to recognize the safety aspects of high voltage. High power hybrid and electric vehicles of course exceed the 60 V maximum, but not with exposed wire as we see with 14-V components. Considerable extra expense due to double insulation, ground-fault sensing, and color-coded cabling is required to exceed the 60-V level. The 42-V PowerNet (Fig. 6) is an attempt to provide a high-voltage standard below the 60-V threshold [4]. This particular standard allows a 4-V cushion between the maximum load dump of 56-V and the generally accepted 60-V safety maximum. For most chemistries, however, the overcharge requirement demands that the nominal voltage be less than 56 V; in the case of lead-acid batteries, for example, it is commonly accepted that an 18-cell system would correspond to this 42/56-V PowerNet standard.

4.3. Voltage limits

The voltage sag during operation of the vehicle is also important. In the case of a 36-V system, engine-on voltage cannot drop below 30 V without becoming a customer satisfaction issue as electrically powered devices such as blowers and lights slow and dim. Likewise, the voltage cannot drop below 21 V during an engine start event without having an impact on vehicle electronics.

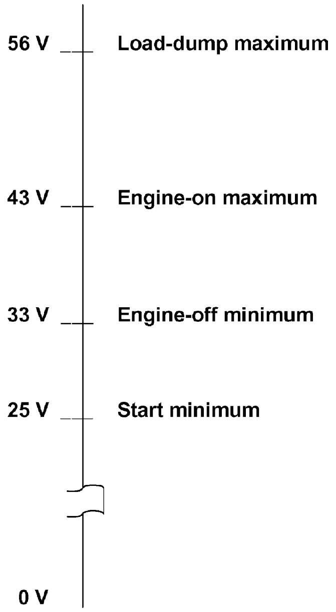

Fig. 6. The 42-V PowerNet voltage ranges. Start minimum is the lower window of voltage acceptable to the vehicle system; engine-off minimum is the lower voltage acceptable to the vehicle system while the vehicle is in the key-on state; engine-on maximum is the maximum voltage, while the engine is on and charging the battery; load-dump maximum is the upper extent of voltage during surges due to loads coming on-line.

Even after a new higher voltage standard is accepted, there will be a need for a 14-V source on a 42-V vehicle until electronics, switches, lamps and other components complete the transition. This could be supplied through either a 42/14-V converter, a separate battery, or a low-voltage tap off the high-voltage battery. The last-mentioned approach would imply additional equalization electronics if cells are charged in series.

5. 42-V features

5.1. Architecture

The architecture of the hybrid battery is shown schematically in Fig. 7 and is expected to contain a number of additional features over that of the current 14-V systems. With the greater number of cells, some form of charge management and equalization will be needed to maintain the battery. This will likely entail current, temperature and voltage sensors that all communicate through the controller area network (CAN) or at least via a local controller. The higher voltage and power capability may also necessitate a fuse and contactor to isolate rapidly the battery in the event of an accidental hard short to chassis or during long stand times. Thermal management may be passive depending on the chemistry, duty cycle and environment, but the escalating costs, temperatures and aggressive duty cycles may require some form of active thermal management such as a fan or a ram-air manifold.

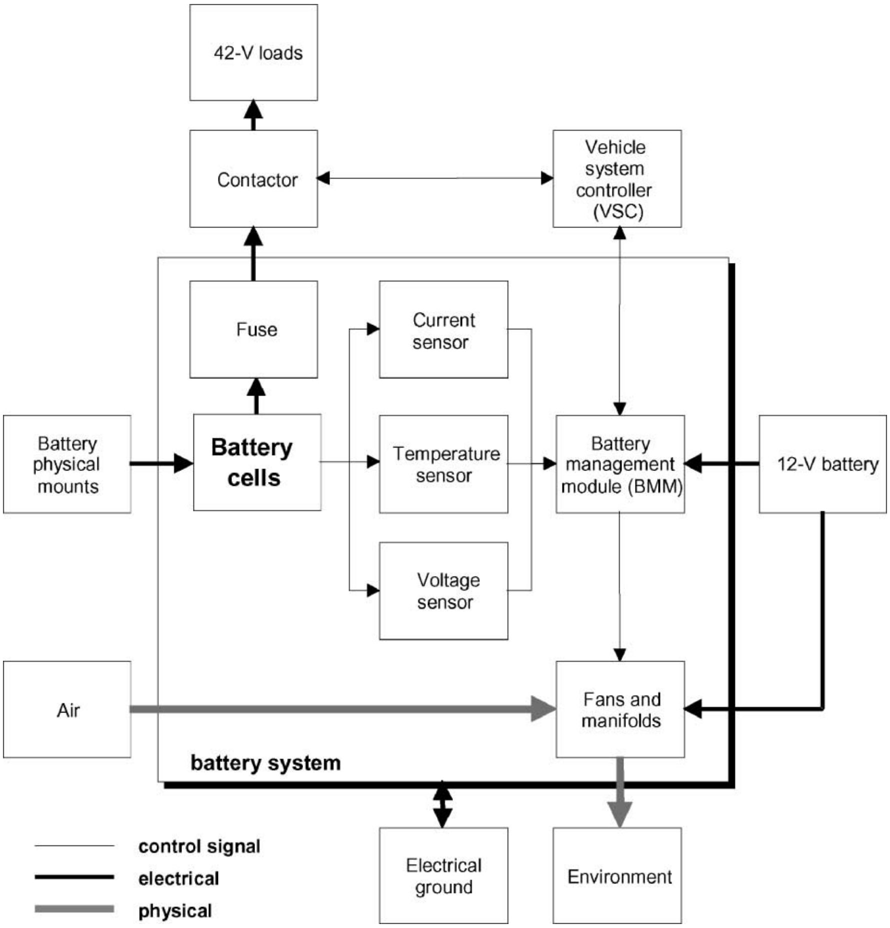

Fig. 7. Typical architecture of high-voltage battery. Ground and communications to devices external to battery system not indicated.

5.2. Thermal management

It is expected that the 42-V automotive battery will reside in the engine compartment. Ohmic losses on the electrical distribution cable at higher voltage for the same power will be less, however, and will thus allow remote placement of the battery in a less hostile environment. Locations such as underseat, wheel wells or the cargo compartment are all possibilities, although some of these areas are often preallocated and well-defended by the vehicle program. Serendipitously, though, many of these packaging alternatives permit improved thermal management due to the absence of proximal heat from the engine.

5.3. Controls and diagnostics

Future products such as CAN-controllable voltage regulators will allow more precise control of the voltage demands of the battery. Moreover, any data available on the CAN, e.g. ambient temperature or engine speed, will be easily available.

The need for self-diagnosing components is a corporate directive for many automobile manufacturers and actions are underway to bring all components into compliance. Self-diagnosis is appropriate for all service items, particularly for such a critical but limited life component as the battery.

6. Conclusions

The preceding discussion highlights the following issues on the choice of future vehicle operating voltage.

1. Electrical system peak loads of 2 kW are near the maximum capability of 14-V standards.
2. Future peak automotive loads will be much higher than 2 kW, possibly maturing at 10 kW or more.
3. Maximum electrical efficiency occurs at higher voltage, but safety dictates that a 42-V nominal maximum standard should be used.
4. The 42-V architectures will entail advanced controls, thermal management, and more complex system architectures.

Thus, while the details are not complete, it is likely that consumer demand for electrical features will force the automotive industry to a new, higher voltage standard.

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