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Review

The challenge to fulfill electrical power requirements of advanced vehicles

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Abstract

In this paper, we will analyze the power requirements of advanced vehicles and assess the likelihood of the top power-source contenders to meet those power requirements in the foreseeable future.

Keywords: 42 V automotive systems; Hybrid electric vehicles; High-power batteries; VRLA; NiMH; Li ion

1. Introduction

The development of vehicles with electrical power train can be traced back to the turn of the 20th century. In the 1970s, rising concerns relative to energy supply sparked some interest in the development of the all-electric car. It is clear that the limitations of battery technology were the cause of the lack of commercial success for those electric vehicle developments in the mass automotive market. In the 1980s, the concerns about energy supply were somewhat subdued and the interest in electrical power train development this time stemmed from the desire to reduce pollution. In Europe, the focus shifted to the development of hybrid electric cars capable of limited electric-only drive. In the US, the Zero-Emission regulations issued by the California Air Resources Board (CARB) in 1990 forced the largest automakers to try, once again, to develop a battery-powered all-electric car. In spite of significant advances in vehicle and battery engineering, the all-electric car is still considered a largely inappropriate solution for the average car driver.

In the late 1990s, however, two new drivers sparked a renewed interest in advanced-vehicle development.

(a) The growing concern that CO_2, a by-product of burning fuel, contributes in a major way to global warming, which spurred the appearance of governmental regulations aimed at reducing CO_2 emissions.
(b) The increased use of electrical power on board modern vehicles, which has brought the power requirements of high-end vehicles close to the limit of the capacity of the current single 12 V SLI battery and Linden generator.

These two market drivers were the motivation for the various technical approaches that are reviewed in the next section, along with their specific electrical power requirements. High-power battery technology is examined in the following section, and the battery technology most likely to address each group of requirements will be reviewed last.

2. Vehicle electrical functionality classes

The future vehicles that will require a battery more advanced than today's 12 V SLI battery can be divided into at least seven categories as follows:

1. 12 V dual-battery system;
2. 42/14 V electrical systems with 'upscale' Starting Light Ignition and Power Ancillaries (SLIPA) battery;
3. 42/14 V electrical systems with stop/start;
4. 42 V soft hybrid (launch-assist);
5. 42 V mild (power-assist) hybrid;
6. high-voltage power-assist hybrid (with or without electric range);
7. plug-in hybrid (with electric range).

2.1. 12 V dual-battery system

This is the lowest-cost, lowest-risk approach to providing additional power for new vehicle ancillaries. The dual-battery system will improve system reliability and increase maximum power and available energy. Such a system could be coupled with an improved 14 V alternator capable

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of a 3 kW output and possibly more. Some manufacturers are even considering two traditional 2 kW alternators. The dual-battery system is already offered on high-end cars in Europe and is likely to spread to more economical vehicles. This design can even support a stop/start function. However, the reliability of the starter could become a problem.

2.2. 42/14 V upscale Starting Light Ignition and Power Ancillary

As electrically driven ancillaries, designed to improve comfort and drivability, find their way into the vehicle fleet, power requirements and energy consumption are increasing accordingly. Increasing the electrical system voltage makes it possible to power those ancillaries without increasing the currents. In some cases, the ancillaries themselves work more efficiently at higher voltage, which means that either a 36 V battery or an expensive dc-to-dc converter from 14 to 42 V will be needed.

2.3. 42/14 V electrical system with stop/start

The stop/start function, which is designed to shut off the IC engine during stop to save fuel and possibly reduce the noise level in the cabin, places additional demands on the battery. Of those, the most important one is that of having to support ancillary loads during engine-off idle stand. Depending on the magnitude of those loads, the most significant of which is air conditioning, and the duration of the stop, 5–50 Wh (1–2.5 kW for 20–200 s) could be used per stop event. Other new requirements include supporting an increased number of engine start events per drive, and ensuring higher reliability as the vehicle will now have to be started in traffic.

2.4. 42 V soft hybrid (launch-assist)

This design adds soft electrically assisted launch from stop as well as charge recuperation during regenerative braking to the 42 V stop/start vehicle. It uses 4–10 kW of power for launch for 0.2–2 s. During regenerative braking, the battery should accept 4–10 kW during a 2–5 s period. If we use 6 kW for 1.2 s, a single acceleration event only consumes 2 Wh. The most severe requirement is charge acceptance, which forces the battery to operate at intermediate state-of-charge (SOC). The combined acceleration and charging loads can generate additional heat, which has a negative impact on battery life and could create a need for an expensive heat-removal system.

2.5. 42 V mild (power-assist) hybrid

In this design, the electrical motor is used for longer periods and more frequently. Typical values are 6–10 kW for 3–10 s. Regenerative braking and idle stop/start requirements are the same as those of the launch-assist design. Additionally, while electrical power is only used during launch from a stop in the launch-assist design, here electrical power is also used during low-speed acceleration at low torque. Such a power boost from the electrical motor facilitates the down sizing of the IC engine, which brings corresponding fuel consumption, weight, and volume savings.

If we use an average power output of 8 kW for an average duration of 6–9 s, we obtain an energy consumption of 13–20 Wh per acceleration event in addition to the energy consumed during idle stop. Just as importantly, duty cycle is considerably higher as several acceleration events are likely to happen per mile in city driving. Car companies are requesting a cycle life of 200,000–400,000 cycles or more over the life of the car for this application.

2.6. High-voltage power-assist

As the power requirements for electrical systems become more stringent, and the duration of the acceleration boost and frequency of use of the electrical assist acceleration increase, it is becoming more efficient to raise the system voltage. In this case, the low-end requirements overlap those of the 42 V mild power-assist, while at the high end, usage power values of up to 60 kW with durations of up to 20 s have been considered in several advanced vehicle designs. If we use a moderate value of 20 kW for 15 s, energy consumption per acceleration event amounts to 50 Wh. With a more powerful electrical motor, the electrical system is now capable of accepting power as high as 60 kW for a sports utility vehicle (SUV), a requirement that is also applied to the battery.

2.7. Plug-in hybrid (with electric range)

This design is also termed “full hybrid”, which refers to the fact that the vehicle can be driven in electric-only mode with full power and functionality, albeit for a limited range. The electrical power requirement depends on vehicle weight and is above 70 kW, even for a compact car, and more than twice this value for a full-size SUV. Energy consumption depends on the desirable electric range requirement. For a mid-size car with a power consumption level of 300–400 Wh per mile, it translates to 3–4 kWh of usable energy per 10 miles of electric range.

While the absolute power requirement is high due to the increased size of the battery that is needed to support the electric-only driving range, the relative power requirement in W/Wh is lower than that of the power-assist designs.

Table 1 summarizes the advanced-vehicle electrical system classes and their key battery requirements.

3. Battery technologies

We will now review the battery technologies that are competing for the advanced vehicle market. We have divided

Table 1
Energy and power requirements for advanced vehicles

	Designation	Main/added requirements	Voltage (V)
Starting light ignition	SLI	Cold start	12
SLI + PA	SLIPA	Alternator assist	12 → 42
SLIPA + stop/start	ISS	Frequent start Reliability Energy drain in key-off situation	12 → 42
ISS + launch-assist	Soft hybrid	Regenerative braking Intermediate SOC operation	42
SH + accelerate assist	Mild hybrid	High power cycling	42 → higher
MH + extra duration	Power-assist	Extended high power cycling	>100
PA + electric range	Full hybrid	Extended energy cycling	>100

them into eight categories as follows:

1. flooded lead acid;
2. valve-regulated lead acid (VRLA);
3. nickel-metal hydride (NiMH);
4. Li ion;
5. other batteries;
6. ultracapacitors;
7. fuel cells;
8. hybrid power sources.

3.1. Prospects of flooded lead acid

The SLI flooded lead acid battery is a mature low-cost technology. It enjoys commodity status with a cost approaching US$ 30 kWh^{-1}, which is well below that of any of the other contending technologies.

It is an existing product with known performance and well-established logistics and manufacturing methods, and with ample unused capacity. The battery is also relatively robust at extreme temperatures.

However, the current technology only has limited cycle life, poor charge acceptance, and moderate power at about 200–400 W/kg. Additionally, the presence of free acid and possibility of leakage are safety concerns.

3.2. Valve-regulated lead acid

The VRLA battery of the absorbent glass mat (AGM) design has enjoyed considerable growth in the industrial stationary application, and has more recently entered the 12 V automotive market. Its semi-sealed design eliminates the concern with acid leakage. The technology also offers superior power to that of the flooded design as well as superior vibration tolerance and cycle life. Key features for high-power automotive usage include:

- 300–600 W/kg at 60–80% state-of-charge;
- best power at low temperatures;
- limited charge acceptance particularly if the battery sits for a few minutes after discharge pulse as shown in Fig. 1;
- relatively steep dependence of power on SOC;

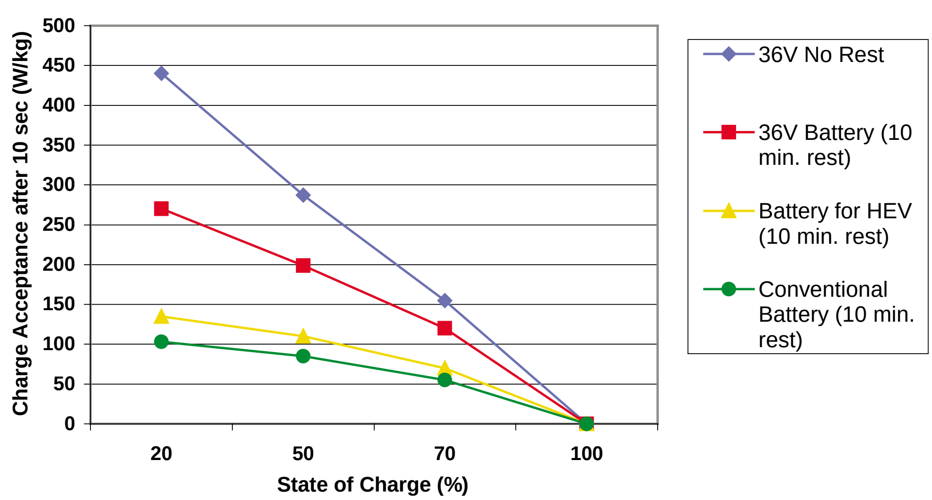

Fig. 1. Charge acceptance for Yuasa's VRLA batteries.

- capacity turnover of 400–1000 at around 1% depth-of-discharge (DOD), which translates to <100,000 1% depth-of-discharge cycles.

The cycle life depends on several factors, including:

(a) depth-of-discharge, which affects material shedding;
(b) charge rate, which can affect venting;
(c) operating temperature, which affects corrosion rate and venting;
(d) average state-of-charge, which affects sulphation, a process whereby a high impedance surface develops on the negative active material if it is left for some duration at a low state-of-charge. Such a build-up prevents future utilization of the material and results in loss of capacity and power.

The main technical challenges for the VRLA technology are to improve charge acceptance and cycle life at intermediate state-of-charge. Additionally, for high-volume production, it will be necessary to improve reliability and reduce cost.

3.3. Nickel-metal hydride

With only 12 years of field experience in any application, the cycle life capabilities of NiMH batteries have proven quite reliable. Power levels, reaching 1000 W/kg over a relatively wide state-of-charge range, are impressive, and reliability in both EV and HEV applications has been good.

In spite of the high power at room temperature, the output power drops sharply with the temperature, as shown in Fig. 2, and is inferior to that of VRLA below about 10 °C. This makes it difficult to rely on NiMH as the only starting battery for cold-morning starts. If used as a single starting battery, it needs to be larger than a lead acid battery would need to be to perform adequately in those circumstances. The rate-limiting step at low temperature relates to surface impedance at the negative electrode's particle interface. While it is possible to modify the particle surface to enhance low temperature output, it has been difficult to implement such improvements without negatively affecting corrosion and self-discharge rates. Fig. 2 display power characteristics of Panasonic EV energy NiMH batteries versus temperature. Two sets of data are shown: (i) circa 1997 cylindrical design; and (ii) circa 2000 prismatic design.

Poor charge efficiency at high temperatures has also been a significant drawback with this technology. Indeed, until about 1999, the practical maximum charging temperature was about 45 °C. This limit was raised by about 10–15 °C during the last couple of years with the introduction of Lanthanum-based additives, which suppress the undesirable early oxygen evolution at the positive electrodes.

The challenges for this technology include reducing cost significantly, supporting a 10-year life in the field, improving power at low temperatures and charge efficiency at high temperatures.

3.4. Lithium ion

This technology has improved remarkably in 11 years of commercial production for the consumer market.

Its key features include the following:

- power at the cell level is more than 2000 W/kg;
- energy efficiency is high;
- charge acceptance is good;
- power at low temperatures is high in W/kg, but only moderate in W/Wh.

The power characteristics of a Shin-Kobe Li ion cell are shown in Fig. 3.

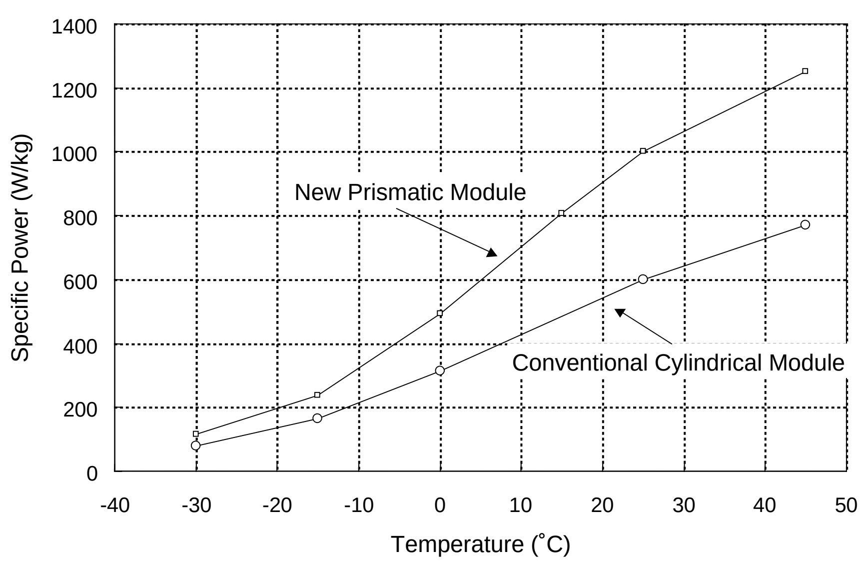

Fig. 2. Power characteristics of Panasonic EV energy NiMH modules at 60% SOC.

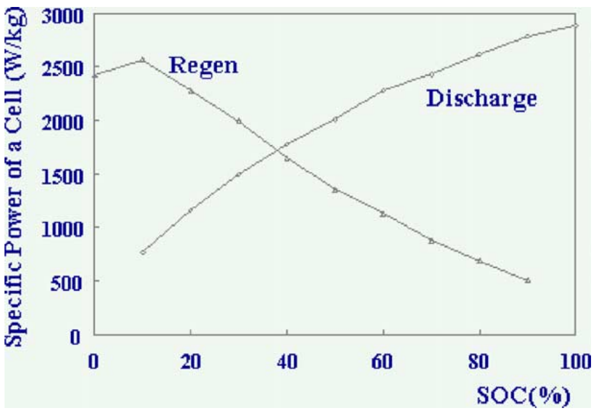

Fig. 3. Specific power of Shin-Kobe's 3.6 Ah $LiMn_2O_4$ cell, at 25 °C.

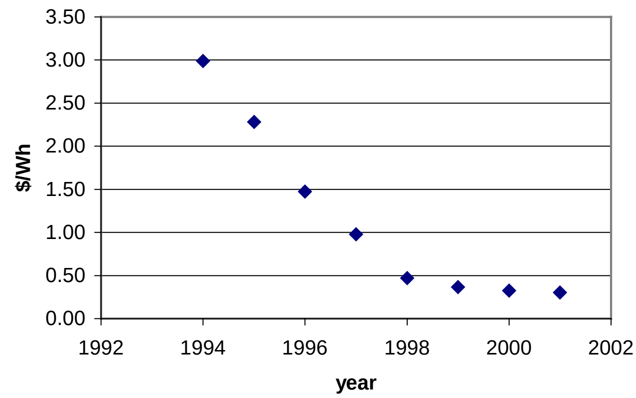

Fig. 4. Price curve of cylindrical Li ion cell.

Key challenges for success in the automotive market include: (i) achieving a significant reduction in cost, to match or surpass that of NiMH; (ii) improving operating life, particularly for the $LiMn_2O_4$-based cathode, from the current 3–5- to a 10-year life in the vehicle. While laboratory data that can be extrapolated to potentially suggest a 10-year operating life for the $LiNiAlCoO_2$-based cathode have recently been shown, it is still unclear whether such data can be realized with a low-cost module design and production processes. In addition, the technology suffers from limited tolerance to abuse as overcharge could cause cell explosion. The abuse tolerance of the $LiNiCoAlO_2$ is particularly weak.

The commercial challenges to using Li ion batteries in automotive include the following:

- establishing high-volume manufacturing of thin electrodes at high yield;
- achieving safety under abuse ;
- developing effective low-cost electrical control;
- achieving a lower cost than that of NiMH, which may require several breakthroughs in materials.

To the advantages of this technology are added the tremendous R&D resources invested by material developers, battery companies, academic and public laboratories. Cost reduction, which is a result of such R&D activity and volume increase, for cylindrical Li ion cells in US$/Wh during the last 8 years is shown in Fig. 4.

3.5. Other "advanced batteries"

We are not aware of any other battery technology that could seriously contend for this market in the foreseeable future (8 years and beyond). The following list includes some of the other types of battery that have been proposed and their major limitations.

- Li ion gel: Its advantages over those of the standard Li ion battery are questionable, while power capability and manufacturability are inferior.
- Li metal polymer: It is far from proven, even for less demanding designs and applications.
- Ni/Zn: Older than NiMH and Li ion, but with limited life and charge rate.
- Na/NiCl2 (zebra): Low power.
- Zn/Air: Low power, complex infrastructure, and, pending on design, questionable life.

3.6. Ultracapacitors

A device that uses high-surface-area symmetrical-activated carbon electrodes with organic electrolyte shows some promise. Its high specific power, in the range of 5000 kW/kg, is its main attribute. It also has good potential for high cycle and shelf life, and delivers its high power over a wide range of operating temperatures.

The use of high-surface-area activated carbon, currently priced in the range of US$ 100 kg^{-1}, is a significant obstacle. Additionally, ultracapacitors store very little energy <5 Wh/kg, and necessitate cell balancing due to the difficulty of ensuring consistent cell-to-cell capacity.

Since the ultracapacitor is only attractive as a power-assist device in parallel with a lead acid battery, cost reduction is the main challenge.

4. Battery solutions to key advanced vehicle classes

4.1. 12 V dual-battery

This market will remain a lead acid territory. Two flooded batteries, two VRLA batteries or one of each are all possible combinations. Also attractive is the use of an 'energy' battery combined with a 'power' battery. If a stop/start function is offered at 12 V, energy management and state-of-health indication will be needed.

4.2. 42 V Starting Light and Ignition and Power Ancillaries

This is a low-cost system, and flooded lead acid or VRLA are the only economical contenders.

4.3. 42 V with stop/start function

This is a low-cost approach to improving fuel efficiency in city driving. VRLA is the battery of choice but reliability of start (in traffic!) and the ability to support the use of air-conditioning in idle must be demonstrated.

4.4. 42 V (super) soft hybrid (launch-assist)

For a 15 Wh profile, we have calculated the following:

- 1.5% DOD on a 1 kWh VRLA (35 kg);
- 0.75% DOD on a 2 kWh VRLA (68 kg);
- 3% DOD on a 0.5 kWh NiMH (14 kg);
- 3% on a 0.5 kWh Li ion (11 kg).

VRLA will only be able to support limited regenerative braking since the battery will need to be kept at above 70% SOC for securing acceptable life.

Depending on duty-cycle and charge rate, the life of the current VRLA technology in this application is predicted to range between 1 and 3 years. For NiMH batteries, a 10-year life is within the current capability. Li ion could meet the cycle life with calendar (operating) life being the challenge.

4.5. 42 V (mild) power-assist hybrid

For a 33 Wh duty cycle, we calculated:

- 1.67% DOD of 2 kWh VRLA (70 kg);
- 5% DOD of 0.66 kWh NiMH (18 kg);
- 5% DOD on 0.66 kWh Li ion (14 kg).

However, if used two times per km in city drive cycle or 400,000 times over the 200,000 km life of the car, we expect battery life to be shorter than 1 year for VRLA, 3–8 years for Li ion and 5–8 years for NiMH.

4.6. High-voltage power-assist

The profile of this design is typically more demanding than that of the 42 V mild hybrid. At >100,000 cycles of >5% DOD, NiMH is the clear choice at this time. Li ion will be a contender in the future, but only if life and cost per kW are similar to those of NiMH. The lower weight and better charge efficiency of Li ion are secondary advantages. For this application, due to the high cost of the battery, obtaining a 10-year life with NiMH (or later Li ion) is the main challenge.

4.7. Plug-in hybrids

For an electric driving range of 20 miles, a 6–10 kWh battery will be needed. Thus, battery cost is a significant challenge. Cycle life at higher depth-of-discharge and weight are the key technical challenges. For a moderate duty cycle, VRLA may be the most economical solution; Li ion offers the lowest weight, while NiMH will probably offer the longest life at moderate weight, but high cost. However, we noted that no car companies are seriously pursuing plug-in hybrid configurations at this time.

5. Conclusions

As the battery is becoming a more important component of future vehicle functionality, more advanced batteries will penetrate the automotive markets. We anticipate the low end of the more advanced vehicles to continue to use lead acid batteries only. Yet VRLA designs at 12, and 36 V batteries of both VRLA and flooded design, will gradually replace the existing 12 V SLI technology. For vehicles with hybrid drive train, the lead acid battery can only support very light hybridization, which provides very limited electric assist and fuel efficiency improvement. Even for mild power-assist, a more advanced battery system is required. NiMH is the contender for all power-assist applications, but high cost and limited power at low temperatures are significant drawbacks. Li ion offers the highest specific power, and with it the best prospect for fuel efficiency improvement, but at a higher cost per kW and per kWh, and is less proven in the field. Breakthroughs in Li ion material cost will be required to make it a viable technology for the automotive market. This is also the case for the ultracapacitor.