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Hybrid electric vehicles and electrochemical storage systems — a technology push–pull couple

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Abstract

In the advance of fuel cell electric vehicles (EV), hybrid electric vehicles (HEV) can contribute to reduced emissions and energy consumption of personal cars as a short term solution. Trade-offs reveal better emission control for series hybrid vehicles, while parallel hybrid vehicles with different drive trains may significantly reduce fuel consumption as well. At present, costs and marketing considerations favor parallel hybrid vehicles making use of small, high power batteries. With ultra high power density cells in development, exceeding 1 kW/kg, high power batteries can be provided by adapting a technology closely related to consumer cell production. Energy consumption and emissions may benefit from regenerative braking and smoothing of the internal combustion engine (ICE) response as well, with limited additional battery weight. High power supercapacitors may assist the achievement of this goal. Problems to be solved in practice comprise battery management to assure equilibration of individual cell state-of-charge for long battery life without maintenance, and efficient strategies for low energy consumption. © 1999 Elsevier Science S.A. All rights reserved.

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1. Introduction

Battery powered electric vehicles (EV) have not achieved widespread acceptance and they are far from being a commercial success. Their limited range is not really a concern in most applications. But almost unlimited range on demand of vehicles powered by conventional internal combustion engines (ICE) has become a common experience when using an automobile. With the rare intermission for fast refueling even on transcontinental trips, the endurance of the driver is challenged in the advance of the vehicle. A reduction of this standard will not be accepted. Zero emission vehicles for private use which require attention with respect to route and time planning will hardly be appreciated on the long run, whether their acquisition be based on free decision or sustained by law.

The energy density of available batteries is limited to approximately 100 W h/kg. Thus, compared to the energy of the same weight of gasoline or diesel as liquid fuels, only about 1% of energy is stored in batteries. Energy flow on refueling a gasoline tank provides more than 100 times the kW h/min, compared to the fast recharge of a battery. Mainly, the high efficiency and general applicability of electricity for power, lighting and heating justifies electrochemical storage systems in mobile applications.

Besides that, batteries require care in use to preserve their performance, making maltreatment a costly experience. Therefore, a sophisticated battery management is necessary for thermal and electrical control of the battery.

An electric drive train per se does not provide zero emission. Battery power permits to achieve zero emission locally, as well as fuel cells with hydrogen as the fuel stored on board. Both storage means equally suffer from poor energy density. Therefore, making use of the high energy density of liquid fuel storage, combined with an efficient electric power train, may offer at least greater flexibility in the design of the vehicle for high mileage, low emission, low fuel consumption or both. A prerequisite is an efficient energy conversion of the liquid fuel into electric power.

2. Development of hybrid electric vehicles (HEV)

Three ways are considered for efficient on board energy conversion of high energy liquid fuels to electric power:

(a) Hydrogen production by a reformation process and use in a fuel cell,

(b) The direct methanol fuel cell, with less energy density of the liquid fuel, compared to gasoline,

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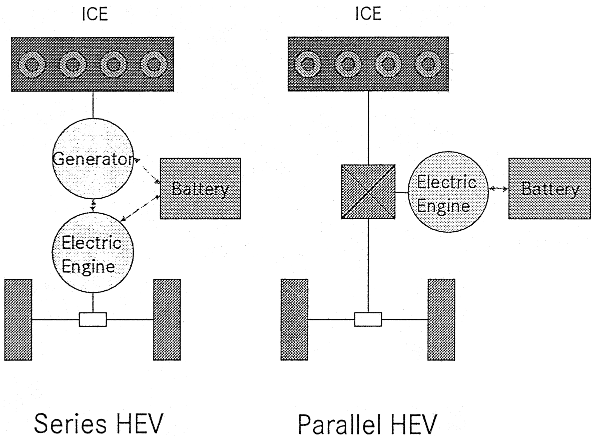

Fig. 1. HEV drive train examples.

(c) Producing electric power by an ICE-alternator unit for intermediate storage in a battery and adding to the efficiency of the drive train, combined with storage of regenerative braking energy.

The last option is the least demanding with respect to the technology development required. With two storage units (fuel tank and battery) and two energy conversion units (ICE and electric motor), this system is in conformance with the definition of a hybrid drive train. In principle, all components required for the drive train are available and are based on a more developed technology than both fuel cell technologies considered.

The potential of HEV to reduce emissions and to increase mileage has already been demonstrated with many prototypes of different kind, and with the Toyota ''Prius'' as the first HEV built in series [1]. The battery as a key component, however, requires more development effort to be ready for widespread application in HEV.

2.1. Types of HEV

Adding an ICE-alternator unit to an EV to charge the battery results in a *series HEV*. Traction power for the drive train is solely provided by the battery and the electric motor; the power transmission and control is electric. Thus, no reduction in motor and controller dimension, and only minor reduction in battery capacity is possible (Fig. 1).

In a *parallel HEV*, the electric engine and the battery are add-on's to the conventional drive train. They assist the mechanical drive train on acceleration and accept regenerative energy by braking, and their contribution can be designed to a defined level. With the split power drive train demonstrated by Toyota [1], the torque of ICE and electric motor are combined by a planetary gear, which permits to select the power distribution between the two branches of the power train.

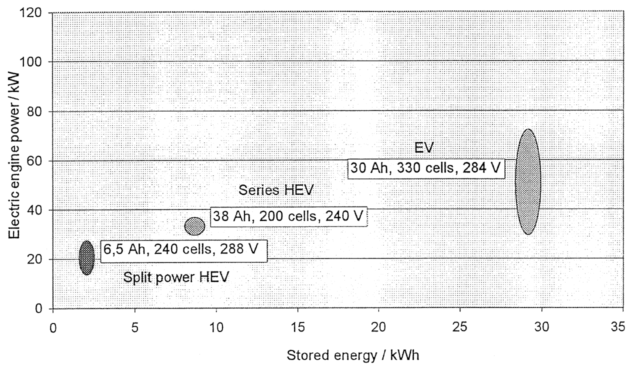

Fig. 2. Examples for battery configurations for different EV and HEV drive trains.

2.2. Merits of the various HEV types

With series HEV, the EZEV (equivalent zero emission vehicle) level of tail pipe emissions can be maintained. Fuel consumption is only marginally less than for the conventional ICE drive train, if the performance is kept at the same level, and costs are high, according to the high power electrical components [2], associated with substantial weight increase, too. For the ICE, there is only limited potential for cost savings, compared to the conventional drive train.

Trade-off reveals better emission control for series hybrid vehicles, while parallel hybrid vehicles with various drive trains may significantly reduce fuel consumption.

The series HEV: eases flexible selection of components, provides on-board power with optimum efficiency, meets equivalent zero emission vehicle (EZEV) standards.

The parallel HEV: permits application of low power components, if, for zero emission driving, only limited speed and range is requested.

At present, costs and overall performance are in favor of parallel hybrid vehicles making use of small high power batteries. Energy consumption and emissions benefit from

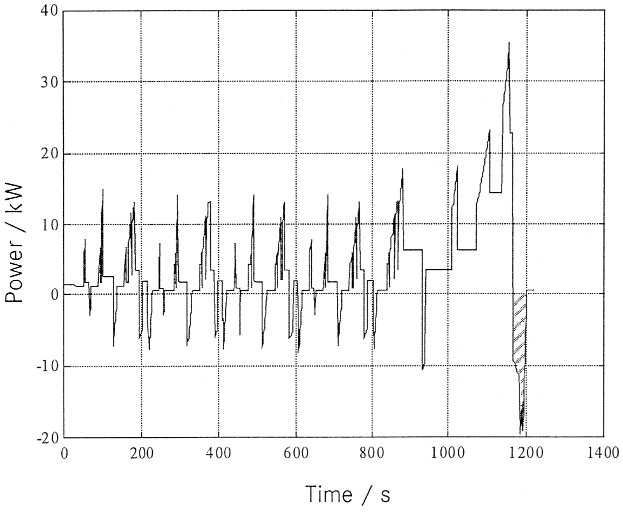

Fig. 3. Power profile of a 1130 kg car on NEDC.

Table 1
PNGV definition/requirements of batteries for HEV

	Power assist, fast response engine	Power assist, slow response engine	Dual mode
Energy, kW h	0.3	3	8
Peak power, kW	25	65	65
Power to energy ratio, h^{-4}	83	22	8
Mass, kg	40	65	115

regenerative braking and smoothing of the ICE, with only limited additional battery weight.

3. Battery requirements for HEV

Fig. 2 shows the stored energy for three examples of batteries and the power of the electric drive train within different types of drive trains. For the EV battery (ZEBRA system for Mercedes-Benz A class EV), three parallel strings of 110 cells make up the battery. As an example for the series HEV battery, a NiMH (Nickel oxide/Metal hydride) system from DAUG is taken, with about 30% of the EV battery capacity, but not much less peak power capability [2] (Mercedes-Benz C-class series hybrid). The parallel HEV battery is represented by the Toyota ‘‘Prius’’ NiMH battery [3]. The specific power of the cells increases from EV to parallel HEV batteries.

Table 1 reports on the HEV battery requirements, as defined by the ‘‘Partnership for a new generation of vehicles’’ (PNGV). While the requirements of the slow response and dual mode batteries are demanding but realistic, the power assist, fast response battery, with a power to energy ratio of 83, appears to be improbable.

Batteries and the electric motor belong to the costly components of the HEV drive train. For a cost effective solution, it is adequate to look for the minimum of energy stored, and for the maximum power necessary to be handled, just meeting the essentials for fuel economy and emission control. These are

- regenerative braking energy and power uptake
- power in the power assist mode of the electric motor to effectively slow down the response of the ICE.

As an example, Fig. 3 shows the power profile of a typical small size car. For a vehicle with 1130 kg of total mass at the ‘‘new European driving cycle’’ (NEDC), the maximum energy to be accepted and stored during regenerative braking is about 100 W h, as indicated by the hatched area in Fig. 3.

The battery exemplified by the power assist fast response PNGV type seems to be an adequate choice with respect to the peak power (Table 1). However, considering the cycle life of the battery, 100 W h to be stored should not constitute more than 10% of the battery capacity, to assure more than 100,000 cycles during a vehicle life time. This is a very crude estimate, because few data indicating a relationship of cycle number on depth-of-discharge (DOD) are available with statistic significance, together with all random parameters that influence cycle life. However, a 1 kW h rather than a 0.3 kW h battery, as suggested in the PNGV requirement, is recommended. The power-to-energy ratio demanded for according to Fig. 3 would then be 20, which is at the limit of present NiMH cells.

Battery voltages for efficient electric drive trains are required to be in the range of 200–300 V. For the two more advanced battery systems, NiMH and Li-Ion, and a 1 kW h, 200–300 V battery, the cell size for all-in-series connected cells would be as presented in Table 2.

Summarizing the technical battery requirements for a cost effective HEV, the following data are requested (Table 3).

With these figures, battery systems weighing 50 to 100 kg, depending on the car size, can be anticipated, with sufficient cycle life to perform adequately during the lifetime of the car.

4. Technologies for HEV batteries

To meet the targets defined in Section 3, scalable technologies which are adaptive to the power demand are needed. Referring to Fig. 4, NiMH is obviously suited for that purpose, as it covers a range of power-to-energy ratios

Table 2
Cell size for 200–300 V, 1 kW h power assist HEV battery

	NiMH	Li-Ion
Cell number	167–250	56–84
Cell capacity, A h	5.0–3.5	5.0–3.5

Table 3
HEV battery requirements

Specific power (discharge)	1 kW/kg
Specific power (charge)	1 kW/kg
Specific energy	40–50 W h/kg
Total energy stored	1–3 kW h
Battery voltage	200–300 V

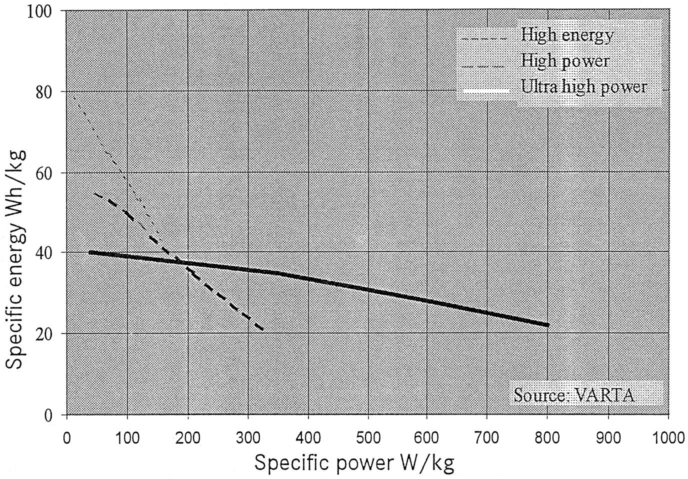

Fig. 4. Ragone plot for nickel-metal hydride ultra high power to high energy cells.

of 2 for high energy cells, and up to 20 for ultra high power cells.

The Li-Ion system [4], not available to date in the same state of maturity, outperforms the NiMH system with respect to energy density and high power capability. For premium type consumer applications, its market share increases steadily at the expense of NiMH cells.

As figured out in Table 2, the cell sizes required for HEV batteries are in the range well known from consumer applications. Of course, the typical cylindrical consumer cells need a redesign to enhance their current capability for HEV use. Terminals and tabs have to be engineered properly, as well as safety elements, at cell level (burst disks and the like). But with the ultra high power density cells in development, exceeding 1 kW/kg, high power batteries can be provided by adapting a technology closely related to consumer cell production.

For the cylindrical cells with spiral wound electrodes, Table 4 presents data which are representative for the state of the art of each system.

Current estimates reveal that the cost per kWh for ultra high power cells will be approximately twice the cost of high energy traction cells.

Further improvement could be achieved with bipolar batteries [5], but at the expense of new manufacturing technologies, and without economy of scale benefits.

Packaging factors of 1.5 for weight, and 3 for volume should be taken into account, moving from cell to battery level.

At the battery level, the most challenging problem is the battery control unit (BCU). For the Li-Ion system, single cell monitoring is mandatory. Due to the tolerance of NiMH cells to overcharge and reversal, the single cell monitoring may be substituted by a module control. A conventional BCU, as applied to traction batteries, will probably not perform adequately because of possible rapid cell heating that might occur in the demanding HEV mode. Relying on thermal sensors, which show some delay in temperature monitoring, could at least promote premature aging of batteries. Also, different rates of self discharge of single cells have to be taken into account by the BCU. After idle periods, an equilibrating charge has to be provided, which is a difficult task to be performed in normal use of the car.

Supercapacitors are reported to have extremely high cycle life and very high power densities. DOD, therefore, is not a concern for cycle life. Their energy density, however, is only about 10% that of batteries, which offsets the advantage in power density. Voltage is a direct state-of-charge indicator, but this in turn requires power conditioning when using supercaps as a storage component. In very small HEV, and together with batteries in EV, super-

Table 4
Typical data of small, cylindrical ultra high power cells

	Pb TMF™ [a]	NiMH	Li-Ion	Supercap
Max. current (2/3 U_0), ambient temp.	100 C_N A	20 C_N A	30 C_N A	5000 C_N A
Self discharge	0.2%/day	0.6%/day	0.3%/day	80%/day
Spec. energy	18 W h/kg	40 W h/kg	60 W h/kg	2 W h/kg
Working temp. range	−20 to +50°C	−20 to +60°C	−10 to +50°C	−20 to +50°C
Cycle life: 80%/3% DOD	100/30,000	2500/> 100,000	600/> 100,000	> 200,000

[a] Trade mark of Bolder Technologies.

caps have been tested. Their future use for hybrid application seems to be dependent on cost issues for high power storage in comparison to high power battery systems.

5. Conclusions

While the early development of HEV was governed by the requirement to extend the range of EV, more recent activities make use of the various options of HEV to reduce emissions and fuel consumption in a flexible and purpose-oriented design.

High power batteries provide the basis for this target, with power-to-energy ratios >20 on charge and discharge, and at reasonable cost. Manufacturing technologies derived from consumer type cylindrical cells offer a tremendous increase in power density for the cell capacity range of approximately 3 to 10 A h, as requested by car size and the type of application. For NiMH and Li-Ion cells, these technologies are proven and ready for use.

For a larger scale HEV battery use, more development work is required with respect to cell packaging and battery control, because up to now thermal management under demanding HEV driving conditions and cell equilibration after periods of standstill are outside the range of experience with these battery systems. Conventional battery assembly methods will not be adequate for a high production level.

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