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Load Leveling Device Selection for Hybrid Electric Vehicles

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ABSTRACT

An important component in many hybrid electric vehicle (HEV) concepts is the load leveling device (LLD). The best type of LLD for HEVs is under debate. This paper identifies the important concept selection criteria for the three leading types of LLDs being considered for use in HEVs. The performance of electrochemical batteries, ultracapacitors, and flywheels is compared using these criteria. The concept selection methodology indicates that at the present time flywheels show the most promise for development for use in a hybrid electric vehicle. The use of this type of selection methodology is a powerful tool in identifying concepts worthy of development as well as determining performance criteria in need of improvement within each concept.

INTRODUCTION

The motivation for the development of hybrid electric vehicles (HEVs) comes from multiple sources. First, there are the state governments. In 1990, the California Air Resource Board passed legislation imposing strict ultralow emission standards [23]. Consumers also motivate the automakers to pursue hybrid vehicle technology by urging industries to produce more environmentally friendly products. Another influence is the federal government. The Partnership for a New Generation of Vehicles (PNGV) is a cooperative between the Big Three automakers and several federal government agencies. It has set goals for the next generation of vehicles. One goal is that new vehicles achieve three times the fuel economy of current vehicles with no loss of vehicle performance. This objective is equivalent to a fuel economy of 34km/l. The PNGV wants these new vehicles to have the same performance and price as current vehicles, and it wants the production prototypes ready by the year 2004 [17].

Currently, the most promising way to accomplish the PNGV objectives is with HEVs. HEVs have a fuel consuming engine to supply average power and an energy storage device to supply peak power [5]. This configuration means the engine only needs to be sized to meet average power demand rather than the peak power demand. In a high-performance vehicle, the ratio of peak power to average power can be as high as 16 to 1 [2]. In a HEV with a series configuration, the fuel consuming engine drives a generator which charges the energy storage device. Also, a regenerative braking system reclaims some of the vehicle's kinetic energy during braking and charges the energy storage device. The energy is used to drive one or more electric motors connected to the wheels.

The energy storage device essentially acts as an energy buffer. It discharges during high power demand and charges during low power demand, thus allowing the fuel consuming engine to ideally operate at one most efficient speed [15]. Because of this intended operation, the energy storage device is sometimes referred to as the load leveling device (LLD). The three LLDs most widely researched are electrochemical batteries, ultracapacitors, and flywheels.

There is currently some debate over which type of LLD is the best choice for use in HEVs. This paper compares the performance of the different types of LLDs that could be used in hybrid electric vehicles and attempts to determine which concept is the best investment of development effort. This paper does not attempt to design a specific vehicle. A design approach is used to compare and select LLDs for development for HEVs and to prioritize the focus of research into LLDs.

DESIGN APPROACH

LLD selection is posed as a design problem for two distinct and complementary reasons. Choosing a LLD for a HEV is a design decision, made at the conceptual stage of design. Also, though research into any LLD will improve LLD and HEV performance, posing LLD selection as a design problem directly links LLD research to the needs of the final customer, the consumer. For application oriented research, knowledge of the customer needs is crucial for resource allocation as well as for provision of a competitive edge as innovations move from the laboratory to the showroom.

As the goal here is the comparison and selection for development of a LLD for a HEV, the usage of the methodology will not be presented in complete detail. Also, as this paper concludes with the selection of the LLD, the methodology will not be presented to completion. For context, a general overview of a design method is presented to clearly put the selection in the context of design. Figure 1 shows a general product design methodology. This approach is consistent with those proposed in Ulrich and Eppinger [24] and Pahl and Beitz [19] as well as those used in industry.

The identified design problem is a hybrid power source for a consumer automobile. Although HEVs are a research topic, their feasibility has been proven with operational prototypes. For the purposes of discussion, a family sized car with a series configuration under urban usage is assumed for a consistent basis of comparison throughout this paper. This usage assumption reduces the customer audience and has implications on customer needs, as applied to a power source. Reducing these customer needs, however, to engineering criteria yields a small set of important design criteria that clearly have impact on many types of automobiles. The conceptual configurations used for comparison is the same for each LLD, as this interchangeability is one of the goals for a HEV.

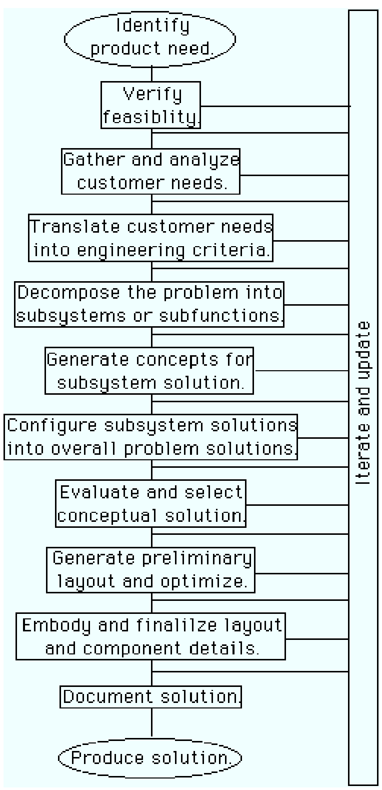

Figure 1. A general design methodology.

SELECTION CRITERIA

The primary traits a consumer looks for in a vehicle that are affected by the LLD include: acceleration rate, fuel economy, level of maintenance, safety, and cost. When these customer demands are translated into engineering requirements and some production considerations are added, the following list of concept selection criteria for an LLD results: specific energy, specific power, efficiency, lifetime, cost, self-discharge, safety, sensitivity to ambient conditions, environmental impact, low maintenance, regulation complexity, and potential for growth.

This list of requirements agrees closely with those proposed by other authors [4,13]. The remainder of this section briefly describes the requirements.

The energy requirement for a HEV is determined by the need to climb hills, pass other vehicles, and operate against headwinds. The energy storage requirements reported in the literature ranges from 0.6-2 kWh [14,7]. It takes about 0.5 kWh to accelerate a family sized car up to highway speeds [14]. Allowing for hills, passing, and headwinds makes the proposed range of values reasonable. The desired point in that range for a given vehicle is determined by the control strategy used by the engine-LLD combination.

The PNGV goal that the acceleration rate of current cars must be maintained in future vehicles establishes the peak output power requirement for the LLD. The use of regenerative braking establishes the peak input power requirement. The range of values proposed for the output power requirement in HEVs is 60-100 kW [14,3]. The precise point in the range is determined by the desired acceleration time and the mass of the vehicle. The input power from the regenerative braking system is approximately the same magnitude as the peak output power. The LLD could be required to accept short duration input currents as high as 20 amps [8].

In the interest of good fuel economy the efficiencies of each component of the power train should be optimized. This supposition includes maximizing the power transfer efficiency, the ratio of input energy to useful output energy, of the LLD. Low self-discharge also contributes to fuel economy. While the LLD only handles transient energy, it would be nice to not have to completely recharge the LLD every time the vehicle is started. The LLD must be able to hold a charge over periods of nonuse.

Long lifetime and low maintenance both contribute to the reliability of the vehicle. One of the failings of current electric vehicles is the need to replace the entire battery pack every few years. Ideally, the LLD would last the entire life of the vehicle and require no maintenance.

Low cost is a desired trait in almost all designs. Another failing of current electric vehicles is their high purchase price. The PNGV set a goal that the next generation of vehicles have comparable costs to current vehicles.

The LLD should also be safe to humans and the environment. The primary safety concerns for the LLD are failures caused by internal factors and by collisions. The safety of the environment involves any toxicity of components and recyclability. Another PNGV goal is that 80% of a vehicle be recyclable.

Since HEVs have to operate in a variety of environments, LLDs must function under a range of ambient conditions. The primary conditions of interest are the temperatures, mechanical shocks, and vibrations experienced in a vehicle.

The power that the LLD supplies must be regulated. The power will need to be conditioned to drive the electric motors which drive the wheels. The complexity of the power flow controller is a factor in selecting an LLD.

The last desirable characteristic is potential for growth. Implementing any of the three types of LLDs requires a considerable investment in a mass production system. That investment is best applied to a technology that will not become obsolete in the near future. The future performance of the concepts must be anticipated based on current research.

After an initial comparison it was found that the requirements that most distinguish between the different LLD concepts are specific energy, specific power, efficiency, life, and cost. These criteria are emphasized during the final evaluation.

LOAD LEVELING DEVICES

Currently, there are three types of LLDs seriously being considered for use in hybrid electric vehicles. These are electrochemical batteries, ultracapacitors, and flywheels. This section presents the performance characteristics of each of the LLD types.

ELECTROCHEMICAL BATTERIES

Electrochemical batteries are the traditional choice for storing energy in vehicles. This fact is primarily due to the decades of experience at using batteries in automobiles. There are at least a dozen types of batteries currently being developed for use in electric and hybrid electric vehicles. Presently, one battery type which seems well suited for use as a LLD is the bipolar lead-acid electrochemical cell.

Specific energy – The strength of batteries is their high specific energies. There are bipolar lead-acid batteries available that have a specific energy of 55 Wh/kg [11].

Specific power – Bipolar lead-acid batteries can have a specific power as high as 830 W/kg [16]. This power is an order of magnitude higher than most other battery types. As a comparison, nickel-cadmium cells have specific powers on the order of 80 W/kg and specific energies of 55 Wh/kg [21].

Efficiency – Because of the high internal resistances of batteries, all battery types possess efficiencies no greater than 75% [22]. The actual efficiency for a battery serving as an LLD will be much less than the value in the vendor data. The capacity and efficiency of electrochemical cells are rate sensitive. Standard battery tests discharge at a rate of C/3, where C is the rate that will fully discharge the battery in one hour. LLD batteries in hybrid electric vehicles have demonstrated discharge rates as high as 30C.

Lifetime --The short cycle life of batteries is a major concern for their use in hybrid vehicles. Bipolar lead-acid batteries that have undergone cycle testing have managed 15,000 shallow discharges [17]. For light vehicle use, this quantity of discharge should result in a battery life of about five years.

Cost --The initial cost of polar lead-acid batteries is about $72/kWh [22]. Distributing this cost over the expected life of the battery yields $14.40/kWh-year of service.

Safety – The safety concerns for lead-acid batteries are overcharging and acid spills. If a lead acid battery is overcharged, explosive gases can build up. Also, if acid leaks from the battery, care must be taken during clean up.

Environmental impact – Lead-acid batteries contain some toxic chemicals; however, the batteries are almost completely recyclable. In addition, since lead-acid batteries are widely used today, the recycling systems are already in place.

Sensitivity to ambient conditions – Compared to other types of batteries, lead-acid cells have good low temperature characteristics; however, they still experience significant loss of capacity during cold weather and a shortened cycle life in hot weather [6]. Mechanical vibrations and shocks should not affect the performance of the lead-acid cells.

Level of maintenance -- The current trend in batteries is towards "maintenance-free," sealed batteries. These batteries require no care other than to be switched out at the end of their life.

Self-discharge – Over short durations electrochemical cells experience only small amounts of self-discharge. Around 1% per day is typical [22].

Ease of regulation – Electrochemical batteries can be difficult to regulate. As mentioned previously, it is dangerous to overcharge a battery cell. A number of lead-acid cells in series and parallel will be necessary to achieve the power system voltage. It is difficult to evenly charge such a stack of batteries. Some cells will receive more charge than others and overcharging can occur [9]. Safe charging requires monitoring of the individual cells.

Potential for growth --There are two other battery types that hold promise for the future. Nickel-metal hydride batteries that have been optimized for specific power are predicted to reach 800-1000 W/kg and have a specific energy of 50 Wh/kg [17]. Initial experimentation with lithium-polymer test cells has demonstrated a specific energy of 250 Wh/kg and peak specific power between 1-2 kW/kg for short durations.

ULTRACAPACITORS

Ultracapacitors, also called double layer capacitors, have developed considerably over the last few years with the advent of new electrode materials to become well suited for use in hybrid electric vehicles.

Ultracapacitors store energy in a polarized liquid layer which forms when a potential exists between two electrodes immersed in electrolyte. The electrodes are composed of materials which exhibit large surface areas per gram of material. Some materials have specific surface areas of 400 to 1500 square meters per kilogram [23]. Some electrodes consist of carbon and metal fibers bonded into a composite fabric.

Specific energy – Prototype ultracapacitors with carbon-metal composite electrodes and an organic electrolyte have exhibited specific energy values as high as 7 Wh/kg [2].

Specific power -- The primary appeal of ultracapacitors is their high specific power. Specific powers greater than 1600 W/kg have been demonstrated [10].

Efficiency -- The very low internal resistance, around 0.2-2 ohms per square centimeter [2], of ultracapacitors gives them a very high cycle efficiency. The energy transfer efficiency is between 92-98% [7].

Lifetime – Ultracapacitors have been tested to 500,000 cycles and experienced only a 20% loss in capacity. This high cycle life means an ultracapacitor LLD should last the entire life of a vehicle.

Cost – Once in mass production, ultracapacitors are expected to cost around $500/kWh [10]. Assuming the life of a vehicle is 15 years, distributing the initial cost over the lifetime of the LLD yields $33.33/kWh-year.

Safety– The only safety concern for ultracapacitors is accidentally coming in contact with the output terminals. The low internal resistance can result in large output currents. The terminals will need to be insulated to prevent accidental contact.

Environmental impact -- The only environmental concern is that the composite electrodes may be difficult to recycle.

Sensitivity to ambient conditions – Ultracapacitors are only very slightly sensitive to temperature and not sensitive to mechanical shock and vibration.

Level of maintenance – There should be no maintenance required over the life of the vehicle.

Self-discharge – There is no information about the self-discharge of ultracapacitors in the literature; however, it was never mentioned as a weakness. Ordinary capacitors can be constructed so as to have very small leakage currents, on the order of picoamps.

Ease of regulation – Care must be taken when charging so as to not to cause a breakdown of the electrolyte. The electrolytes currently used in ultracapacitors have breakdown voltages around 1-3 volts [2].

Potential for growth – Ultracapacitors show considerable promise for the future. There is still much material science research to be done on electrode and electrolyte materials [17]. The specific energy and specific power for ultracapacitors is expected to triple in the long term [11].

FLYWHEELS

Storing energy with flywheels is an old idea that has recently received renewed interest. Much research on flywheels was conducted during the 1970's, but that research was all but abandoned during the 1980's. The recent resurgence of interest in flywheels is largely due to the advent of filament wound composite rotors [1] and high magnetic field permanent magnets [21]. Composite rotors can rotate faster than the old steel rotors because of their increased strength to weight ratio.

Specific energy– The specific energy values for current flywheel energy storage systems range between 28-50 Wh/kg [11,20,25]. The Lawrence Livermore National Laboratory (LLNL) has developed an flywheel battery system for use with hybrid vehicles that stores 1 kWh with a specific energy of 50 Wh/kg [20].

Specific power -- The LLNL flywheel battery can deliver 200 kW with a specific power of 10 kW/kg of system mass [20].

Efficiency – With the flywheel rotating in a vacuum on magnetic bearings, very high efficiencies can be achieved. The energy recovery efficiencies for electromechanical batteries range from 95-98% [17].

Lifetime -- Since the rotor is the only moving part and it has little to no contact with anything else, the flywheel system should have a long service life and be able to withstand a virtually unlimited number of deep-discharge cycles [20].

Cost -- Cost estimates for automotive flywheel systems are hard to come by since none have been mass produced. One estimate suggests a 4.1 kWh flywheel system can be mass produced for $800 per unit [12]. This estimate corresponds to $195/kWh. The flywheel should last the entire life of the automobile. When the cost is distributed over a 15 year life of a vehicle, the yearly cost is $13/kWh-year.

Safety -- The big safety concern with flywheel systems is the possibility of rotor failure. Fortunately, experiments indicate that when a composite fiber rotor fails it turns into a corrosive cloud of hot fibers and small pieces, not ballistically penetrating fragments. Flywheel systems have metal/fiber composite containment vessels which can contain the rotor fibers [20]. DARPA has funded the Flywheel Safety Project to design safe rotors and containment vessels.

Environmental impact -- The only environmental concern for a flywheel system is the difficulty in recycling the composite rotor.

Sensitivity to ambient conditions – A flywheel energy storage system is not sensitive to temperature and vibration. The rotor will have backup ceramic bearings to

	Batteries	Ultracapacitors	Flywheels
Specific Energy(Wh/kg)	55±20	7±1	50±20
Specific Power (W/kg)	830±80	1600±600	10,000±2000
Efficiency (%)	75±5	95±3	96.5±2
Life (cycles)	15,000±0	45,000±0	45,000±0
Cost ($/kWh-year)	14±6	33±6	13±6

Table 1. LLD Concept Characteristics.

prevent damage to the system in the advent of severe mechanical shock loads.

Level of maintenance -- The flywheel should require no maintenance over the life of the vehicle.

Self-discharge -- The magnetic bearings and vacuum give flywheels a low self-discharge rate, about 1% per day. The LLNL flywheel takes over two months to spin down on its own [20].

Ease of regulation – A flywheel battery is an AC machine. The motor driving the vehicle's wheels will most likely be an AC machine. This similarity simplifies the power conditioning. Also, steps must be taken to not overcharge the flywheel. If the rotor is driven too fast, the rim the rotor will expand to the point where it touches the containment vessel.

Potential for growth – The primary focus for future development is in reducing the cost of production. New simpler and less expensive magnetic bearings are being developed. Less expensive fiber winding methods and materials for use in the rotor are also being developed.

CONCEPT COMPARISON

The selection of the preferred LLD concept is done using a selection matrix approach, similar to that proposed by Otto and Wood [18]. In this method, the selection criteria that most distinguish between the concepts are weighted relative to each other. Then, a reference concept is selected (in this case, the battery). The concepts are rated against the reference concept using the values in Table 1. An important feature of this selection methodology is that it accounts for uncertainty in both the performance of the concepts and uncertainty in the criteria weighting. The ranks are expressed as a nominal value and a tolerance. In addition, a confidence value is determined. Additional details about this methodology along with the associated mathematics can be found in Otto and Wood[18].

Every engineer will assign different weights to the various criteria. This selection methodology allows for uncertainty in the weighting factors. The weighting factors and their uncertainty are shown in Table 2. The criteria are weighted fairly evenly. The specific power is weighted slightly more because supplying peak power is the primary function of the LLD. Life is weighted slightly less because, since cost is a separate issue, the predictable replacement of the LLD unit is merely an inconvenience.

A fairly large uncertainty of ±5 is assigned to the first four criteria to accommodate designer discretion. A larger uncertainty of ±10 is assigned to cost because the importance of cost may change as the development process continues.

The lead-acid battery is selected as the reference concept since it is currently the industry standard for use in HEVs. The other concepts are scored based on the data in Table 1. The values and their tolerances were obtained through a survey of the relevant literature. The life estimates for the ultracapacitor and flywheel concepts are listed as 45,000 cycles because this is the assumed number of cycles a vehicle will experience in its lifetime, and the value of surviving beyond this number is debatable. Table 2 shows the concept scoring matrix with the total scores for each concept, the tolerance on each score, and the confidence levels of the results.

The confidence level is a measure of the degree of belief in the results of the scoring matrix. Table 2 shows that the greater specific power, efficiency, and lifetime of flywheels give them the highest score. The confidence level in the battery column is 0.96. This value means that it is 96% certain that the choice of flywheels over batteries is correct. In the same manner, it is 92% certain that flywheels are a better choice that ultracapacitors. Table 2 also shows that the weaknesses of batteries are specific power, efficiency, and lifetime, and the weaknesses of ultracapacitors are specific

		Load Leveling Device Concepts					
		Batteries		Ultracapacitors		Flywheels	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Specific energy	20±5	100	20.0	76.0	15.2	97.5	19.5
Specific power	25±5	100	25.0	164.2	41.1	864.2	216.1
Efficiency	20±5	100	20.0	120.0	24.0	121.5	24.3
Lifetime	15±5	100	15.0	150.0	22.5	150.0	22.5
Cost	20±10	100	20.0	86.5	17.3	100.7	20.2
Total Score		100.0±15.3		120.1±30.9		302.5±278.3	
Confidence		0.96		0.92		N/A	

Table 2. Concept Scoring Matrix.

energy and specific power

To demonstrate the capabilities of the three LLD concepts and reinforce the results of the scoring matrix, Table 3 shows the mass of a LLD unit necessary to meet the energy and power requirements of a HEV. The mass of the LLD is an important parameter because reducing the mass of the vehicle improves the fuel economy. One kWh and 100 kW are chosen as the energy and power demand, respectively, of a representative HEV.

Table 3 shows that the mass of a lead-acid battery pack is determined by the peak power requirement, and 120 kg of lead-acid batteries is needed to meet the power demand. Slightly more mass is needed with ultracapacitors. They are, however, constrained by the energy storage requirement, and an ultracapacitor with a mass of 142 kg is required to meet this requirement. The flywheel LLD is by far the lightest concept. The flywheel is limited by the energy requirement, and the necessary mass is only 20 kg.

Criteria	Battery Mass, (kg)	Ultracapacitor Mass, (kg)	Flywheel Mass, (kg)
Energy Requirement	18	142	20
Power Requirement	120	63	10

Table 3. Necessary LLD Concept Mass.

CONCLUSION

The use of a design methodology for concept selection in this paper provides a clear link between customer needs, design criteria, and research and development needs. In this case, the results indicate a research focus into flywheel LLDs. In a general case, using a customer motivated design approach in this way allows research and development to be focused on results that will have an impact on customer satisfaction, and in turn product and company success, as the research matures.

The performance capabilities of all the LLD concepts are expected to increased as the concepts are developed. For this reason research should be continued on all the concepts. In particular, the specific power of batteries needs to be increased. The specific energy and cost of ultracapacitors needs to be increased, and mass production methods for flywheel batteries need to be developed so that flywheel cost is reduced.

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