HYBRID SHUTTLE BUS USING ULTRACAPACITORS

Jeff Major
Electric Vehicle Institute
Bowling Green State University

Abstract: The Electric Vehicle Institute, College of Technology at Bowling Green State University in Ohio has developed a diesel/electric hybrid propulsion system. This system has been installed in a 27 passenger shuttle bus. This bus has recently been put into shuttle service on campus in order to collect application data, receive feedback from professional operators and provide a demonstration of the suitability of the system for service. This paper describes the hybrid system, explains the operation, and elaborates on the reason for choosing the electrical energy storage system type, ultracapacitors.

Key Words: Hybrid Vehicle, Hybrid Bus, Ultracapacitor, Regenerative Braking and Electric Propulsion

I. INTRODUCTION

A. The System

The Hybrid Booster Drive™, or HBD, is a system which complements the existing propulsion system in the vehicle in which it is installed. That vehicle then becomes a hybrid vehicle, using a combination of two types of energy, fuel and electric. The HBD equipped vehicle is an engine dominated, parallel electric hybrid.

The HBD system is intended for vehicles with missions (or routes) requiring numerous stops and speeds primarily below 35 mi/h. This is ideal for shuttle bus applications. Testing of the prototype on such routes has demonstrated up to 30% increase in mi/gal. Actual savings depend on drive cycle.

The HBD works in conjunction with the internal combustion (IC) powered system. A major benefit of the HBD equipped vehicle is that it will operate under IC power alone if the HBD system is disabled.

The Hybrid Booster Drive™ consists of four component modules: an electric traction module, a motor controller module, an ultracapacitor electrical energy storage module and a supervisory control module which incorporates integral operational software. The HBD supplements the existing IC drive system in the vehicle. At no time does the HBD do it all. The engine always remains running, although it does not work as hard. During braking, the HBD may provide all the stopping power needed, but blends seamlessly and unobtrusively with the existing service brakes as needed.

All four component modules of the HBD™ are scalable in design, require little or no maintenance, and are expected to last the life of the vehicle.

Figure 1. BGSU Shuttle Bus with Hybrid Booster Drive™

B. Operation

The HBD electric motor is close-coupled to a planetary speed reducer which is then connected to a parallel shaft transfer case. The transfer case is coupled to the vehicle's power train via the vehicle's drive shaft, located between the transmission and the rear differential. The reducer transfer case provides a speed ratio reduction. The transfer case also provides a means to clutch the electric motor from the vehicle drive shaft with a 12 volt electrical signal. The HBD supervisory control automatically disengages, synchronizes and re-engages the electric motor from the drive shaft depending on the vehicle speed. The electric motor provides torque for acceleration and regeneration only below 40 mi/h. Above 40 mi/h, the electric motor is disengaged, so there are no loses attributed to the HBD during high speed operation.

The electric motor is an induction motor which is liquid cooled using automatic transmission fluid (ATF). ATF also provides lubrication for the motor bearings and the close-coupled planetary gear box. ATF is contained in an oil sump attached to the bottom of the electric motor. The coolant oil is circulated, via a lube pump, from the sump through a filter and heat exchangers (radiators) and then to the motor and gearbox. The pump is gear driven from the transfer case. This coolant oil is used only for the electric motor and close-coupled planetary box. The transfer case lubricant is self contained.

The electric motor is designed to operate at speeds up to 12,000 r/min. It requires power in the form of three phase alternating current (ac). The electrical energy storage system (EESS) operates on direct current (dc). A three phase full bridge inverter is used to convert the dc to ac and visa versa. This is the main power component of the motor controller. The motor controller operates in flux vector mode with velocity feedback from the electric motor via an encoder (pulse generator) attached to the end of the motor. This control mode allows for four quadrant torque control, although only two quadrants are used in the HBD application, forward rotation, positive and negative torque. The electric motor is not used for vehicle reverse travel.

The HBD supervisory controller monitors state functions of the vehicle systems, both internal combustion (IC) and electric propulsion (EP), and the operator (driver) inputs to determine the torque requirement, both IC and EP. The torques produced by the electric motor and engine are determined by the HBD supervisory controller which communicates with both the motor and engine controllers. The driveline torque is proportioned between the IC and EP to yield required acceleration using the appropriate amount of electrical energy from the EESS and minimizing the torque from the IC engine. This strategy is to reduce the fuel consumption and exhaust emissions.

During the braking event (deceleration) below 40 mi/h, the electric motor produces negative torque, or regenerates. This action converts the kinetic energy of the vehicle into electric energy which is then stored in the EESS, while slowing the vehicle's speed. A sensor is attached to the brake pedal which provides a proportional signal to the supervisory controller which then determines the appropriate torque command to send to the motor controller. The HBD supervisory control is not physically connected to the vehicle electronic brake control or hydraulic system.

Below 40 mi/h, regenerative braking can provide sufficient torque (power) to nearly bring the vehicle to a complete stop. Regeneration captures energy normally lost as heat in the friction brakes. This captured energy can be viewed as free energy because fuel is not used to produce it. The supervisory control is programmed to maximize the amount of energy derived in this method, taking into consideration all conditions. The service brakes (friction) come into use only at very low speed or in the event of an emergency stop.

The energy captured during the regeneration event is stored aboard the vehicle in the EESS. The HBD system features ultracapacitors as the electrical energy storage devices. Ultracapacitors function in a similar manner as would batteries, but store the charge in an electrostatic field instead of using chemical reactions as done in batteries. Because of this, ultracapacitors offer advantages in areas such as maintenance, efficiency, charge rate, temperature range, cycle life and cost. Ultracapacitors are high power devices as compared to batteries, but store less energy, pound for pound. The size of the ultracapacitor system in the HBD is optimized for the vehicle mass and mission. Typically, the HBD ultracapacitor is sized to store energy from one deceleration from 40 mi/h to zero.

The EESS is charged during deceleration. While the vehicle is stopped, the ultracapacitors are at a high state of charge (SOC), ideally fully charged (100% SOC). This energy is then used to supplement the IC engine through the EP for the next acceleration. The IC engine output is held back by the supervisory control, in most cases, to about 50 %. This is done proportionally at different speeds in order to minimize fuel consumption and provide seamless operation.

After the vehicle has accelerated to 35 or 40 mi/h, the energy which had been stored in the EESS is nearly depleted (low SOC). Vehicle operation at cruising speeds or above 40 mi/h is not aided by the HBD. The EESS is intentionally left at a low SOC while the vehicle is cruising so that there will be capacity to store the energy from the next deceleration. The control adjusts SOC and "electric boost" based on the vehicle drive cycle to maximize performance. There are also times when a small amount of energy is siphoned from the vehicle IC driveline and added to the EESS during cruise to adjust the system state. All of these actions are done automatically by the supervisory control.

C. Environmental Benefits

The HBD reduces emissions and increases fuel mileage. These benefits are achieved by allowing the engine to operate at a steadier and efficient load range. In many applications the engine can be downsized to further increase mileage, lower emissions and reduce weight. HBD can be applied to vehicles with diesel, gasoline, CNG, LPG, or 'Clean Diesel' fueled engines.

II. DISCUSSION

Ultracapacitors were selected as the on-board energy storage system for the Hybrid Booster Drive™ (HBD) because this technology offers distinct advantages compared to battery based energy storage systems. These advantages include:

- High charge rates
- High efficiency
- High power density
- Excellent low temperature performance
- Long cycle life
- Long operational life
- No maintenance

As ultracapacitors are used in the HBD system, they are charged each time the vehicle stops. This means they are charged in about 7 seconds. This is a very high charge rate compared to a battery's capability. A peak power of over 150 kilowatts is often seen during regeneration, when the ultracapacitor is charged.

Energy is stored by charging the ultracapacitor and then used by discharging it. As with any physical system, ultracapacitors have losses. More energy is required to charge than will be available on discharge. The ratio is called "round trip efficiency". The round trip efficiency for ultracapacitors as used in the HBD vehicle is approximately 80% [1]. A direct comparison to batteries is not possible because batteries can not be charged as quickly. Typically, batteries have lower efficiency than ultracapacitors. Generally, the efficiency for ultracapacitors is cited to be 95% [2]. Batteries, when used in hybrid applications, are typically 65% efficient [3].

Ultracapacitors are powerful devices. As used in the HBD vehicle, compared to lead-acid batteries, they are about 10 times more powerful, pound for pound.

However, batteries store more energy than ultracapacitors. An equal weight of lead-acid batteries could store 5 to 10 times the energy as could ultracapacitors.

The HBD vehicle saves fuel by using energy normally lost, or wasted, during deceleration. So, the energy storage system, ultracapacitor, is sized to store just this amount of energy. The electrical energy storage capacity is set equal to the kinetic energy of the vehicle at 40 miles per hour. Ideally, the HBD vehicle completely recharges the ultracapacitor system each time it comes to a stop. Then, uses this stored energy to supplement the engine during the subsequent acceleration.

A battery sized to the energy requirement outlined above would be incapable of the power levels needed. Lead-acid batteries sized to handle the power needed for the HBD vehicle would weigh 5 to 10 times more than the ultracapacitor system, and even then not be capable of absorbing all of the regeneration energy during the deceleration. This means that a battery hybrid vehicle would need to dissipate energy in friction brakes or a resistor in order to stop in the required distance. This is energy lost, which can be recovered when using ultracapacitors.

However, such a battery system could propel the vehicle much further, perhaps miles. The ultracapacitor system used in the HBD can only provide launch assist and offers no electric-only propulsion operation.

Ultracapacitors operate over a wide temperature range because they do not rely on chemical reactions as do batteries. Ultracapacitors can function normally up to 65°C and down to -40° with only a slight increase in resistance at the low end. Battery energy and power capability suffers greatly as temperature drops below zero. From 20°C to 0°C, the battery energy is reduced by 35%. Battery energy is reduced down by as much as 80% at -20°C [4].

Ultracapacitors have excellent cycle and operational life. Over 500,000 complete charge/discharge cycles can be expected, as well as a 10 year minimum [5]. The ultracapacitor should last the life of the vehicle, with no maintenance. Batteries, on the other hand, will not last as long. It is generally accepted that at least one complete battery replacement would be required.

The ultracapacitor energy storage system consists of many ultracapacitor cells connected together, in a similar fashion as a battery consists of multiple cells. In the HBD system, several hundred ultracapacitor cells are connected in series to provide the appropriate working voltage, power and energy. Each ultracapacitor cell consists of a sealed container with carbon, aluminum and a solvent. There is no exchange of material from inside the cell to the outside. The ultracapacitor cells are arranged in a "pack" mounted to the chassis of the vehicle. The enclosure for the pack is a durable steel box. There may or may not be ventilation of the pack for thermal management, depending on the type of ultracapacitor used.

Figure 2 shows the ultracapacitor pack and how it is attached to the chassis of the hybrid shuttle bus. The bus uses two of these packs, one on each side of the frame.

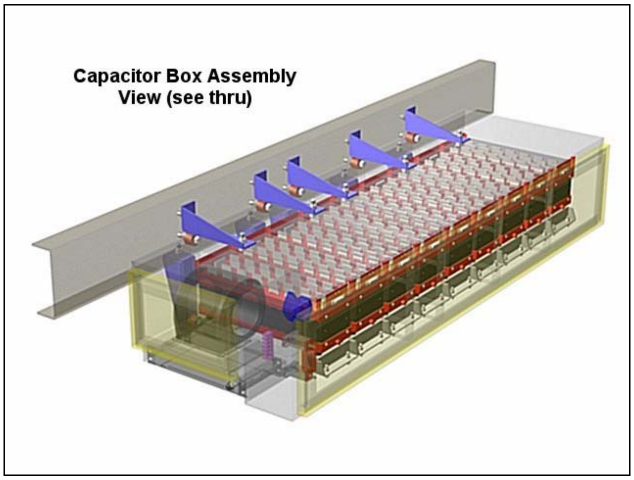

Figure 2. Energy Storage Module As Used on the BGSU Hybrid Shuttle Bus

There are several types of ultracapacitors available on the market and several more under development. Presently, about ten manufacturers offer ultracapacitor product for sale, worldwide. Markets include industrial, transportation, military, power quality and commercial applications. The production base is increasing and the cost is decreasing. This, along with process and technological improvements, will cause the ultracapacitor to displace more and more batteries. The power, size, reliability, durability and life of the ultracapacitor make it the sensible choice in many applications.

III. CONCULSIOINS

The hybrid system developed and installed on the shuttle bus is a proper application for ultracapacitors as the electrical energy storage system. The system saves fuel and reduces emissions by utilizing energy normally lost during braking to assist to accelerate the vehicle. This magnitude of energy is within the capability of a reasonable sized ultracapacitor system. This ultracapacitor system is capable of the power levels required to decelerate the vehicle in the required period while maintaining higher round trip energy efficiency than batteries.

REFERENCES

1. Cohen, Mark. *Top Ten Reasons for Using Ultracapacitors in Your System Designs.* Program Director, Maxwell Technologies.

2. Lev, Frank. *Optimal Hybrid Electric Power Train for Heavy Vehicles and Buses.* Tavrima Limited, unpublished paper. October 1999.

3. Mosely, Patrick T. *High-Rate, Valve Regulated Lead Acid Batteries – Can They Be Suitable for Hybrid Electric Vehicles?* A paper presented at Hybrid Electric Vehicles: Here and Now TOPTEC, New York, May 26-27, 1999.

4. From Product Data Sheet, Power Sonic Sealed Lead-Acid Batteries, web site http://www.power-sonic.com/gencat0103.pdf, January 2005.

5. From Product Data Sheet, PC2500 Ultracapacitor Product Information, Maxwell Technologies, web site http://www.maxwell.com/index.html, January, 2005.

AUTHOR

Jeff Major, Chief Engineer, Electric Vehicle Institute, Bowling Green State University, Bowling Green, OH 43403. Jeff has been with the Electric Vehicle Institute for the past ten years and has been a significant contributor in motor and controller development. Jeff holds a BSEE from the University of Toledo. He has served as a part time instructor at the University of Toledo, College of Engineering in energy conversion and at Bowling Green State University, College of Technology in electronics. Jeff completed eleven years experience in industry with the Prestolite Company, Toledo, OH. He held positions of Product Engineer and Manager of Engineering for the motor group with responsibilities for product engineering and R&D. He has ten US patents issued for motors, related apparatus and vehicle systems. Jeff has extensive experience and expertise in electric vehicles, electromechanical energy conversion and power electronics.