HYBRID VEHICLES IN THE BUS AND TRUCK MARKETS

TOPTEC®: NEW WAYS OF BUILDING BETTER HEAVY-DUTY VEHICLES

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ABSTRACT

The potential of hybrid electric vehicles for reducing air and noise pollution, increasing fuel mileage, and utilizing alternate fuels is well known. No matter how efficient, rugged, or well designed the electric traction drive package is, the on-board energy storage device remains the fundamental flaw of electrical drive systems. Traditionally, this storage device has been an assemblage of lead acid batteries. Integrating battery packs into hybrid vehicles requires complicated maintenance systems plans.

The NASA hybrid Electric Transit Bus (HETB) project has proven the use of highly efficient, long life, low maintenance ultra-capacitors as an energy storage alternative to batteries. Prior to the success of the HTEB, integrating ultra-capacitors into hybrid drives was thought to be a futuristic idea awaiting the development of complicated, expensive, and inefficient buck boost type converters.

In this paper the requirements for a cost-effective ultra-capacitor-based hybrid drive systems and their features are presented. Then the integration of these components into vehicles will be developed. Initially, engine-dominated capacitor assisted parallel booster-driven systems will be presented. Series configurations for hybid vehicles will be described. Finally, futuristic developments such as gas turbine driven and fuel cell powered series configurations will be discussed.

INTRODUCTION

NASA scientists released the results of the first phase of NASA Hybrid Electric Transit Bus (HETB) *Space Bus* project. In the NASA report, published in January 1999, the HETB series hybrid vehicle equipped with ultra-capacitors produced a 21.2% fuel savings for the white book central business district drive cycle over a traditional diesel-powered vehicle[1]. The NASA report extensively documented the performance and commercial potential of a series hybrid ultra-capacitor-driven transit coach. An SAE paper by Palumbo and Waggoner presented the performance, major component features, and implications for an engineered hybrid drive system derived from the HETB project [2]. The 1999 SAE paper introduced potential vehicle manufacturers and their customers to an available cost-effective hybrid drive system that was developed from the components used during first phase of the HETB project.

How these components can be integrated into hybrid vehicles is the focus of this paper. To make the integration easier and allow for systematic model changes as more cost effective options become available, the major components are designed so that the building blocks of the system can be modularized. The integration of the ultra-capacitor, traction drive and the traction controller is a starting point for the process. These three basic modules can be integrated as a booster drive *parallel configuration* using optimized conventional vehicle drive components. A series configuration can also be built with the addition of a primary power unit and electrically-driven auxiliary systems.

ULTRA-CAPACITORS AND BATTERIES

In hybrid electric vehicle designs, some form of electrical storage module is incorporated to reduce the peak power needed to accelerate the vehicle [3]. Up till now, the only available and affordable storage device was the lead acid storage battery. Ultra-capacitors had been considered to be too experimental to become viable. Ultra-capacitors are now available for hybrid vehicle developers [4].

For those who are not familiar why ultra-capacitors are desirable as storage devices for hybrid vehicles an analysis is provided in appendix 1. The data from the first phase of HETB testing demonstrated that ultra-capacitors were superior to batteries in delivering load currents to the traction drive when accelerating.

ULTRA-CAPACITOR-BASED HYBRID DRIVE SYSTEM MODULES

For the application in diverse vehicle types, the system components have been packaged in modules whenever possible. This allows for easier integration into specific vehicle applications. This was done to allow for mass marketing of specialized vehicle applications.

Ultra-capacitor Module Integration-Integrating ultra-capacitors into vehicle designs can be much simpler than batteries. Since capacitors do not require charging and thermal management systems, they can be mounted where battery storage systems would be less feasible. One robust cylindrical capacitor package offered by a supplier requires less capacitor protection and mount configuration requirements than other ultra-capacitor models. In high floor bus designs these ultra-capacitors can be easily clamped below the floor to a frame member similar to a compressed air or conventional fuel tank. Only the inner connections need to be protected. The disadvantage to the cylindrical ultra-capacitor design is in these low floor installations. The large diameter does not allow for sufficient road clearance unless the floor supports are modified and the floor *dimpled.* Since ultra-capacitors increase fuel mileage they can replace fuel tanks. One option is to mount the capacitors on top of the vehicle where natural gas tanks are usually mounted in what is termed *roof mounting*. The disadvantage to roof mounting capacitors is that of the high center of gravity which is similar battery pack roof installations.

Capacitor Storage and Seating Designs-Working with seating manufacturers offers a unique modular solution. Ultra-capacitors could easily be incorporated and sealed into the unused space under passenger seats. Unlike batteries, efficient ultra-capacitors do not require cooling or routine service. Conduit for the power cables could be run below the floor or in ducts along the base of the floor and wall. These conduits would also provide ventilation for the sealed capacitors. In this installation, capacitor connections can be of the quick disconnect type. Seat or capacitor replacement could be made at the same time, quickly returning the vehicle to service. This type of module is unique in that the more passengers, the larger the bus, and, consequently, the more capacitors are built into the system. Such a relationship is a natural development, when more power is needed it is provided.

Under Floor Capacitor Storage-Another ultra-capacitor manufacturer offers a rectangular design that can be mounted between the floor structure in low floor bus designs. Although less robust than the cylindrical design, flat covers below the frame could easily provide the needed protection. The larger the bus the larger the floor area and the more capacitor storage is, agian, naturally provided.

Capacitor and Battery Comparisons-Although capable of high power, each ultra-capacitor stores less energy than a comparable battery. Ultra-capacitors can take a charge and release it at a much faster rate than lead acid batteries. Ultra-capacitor modules can be mounted throughout the vehicle with no concern for temperature control or need for routine service. Catastrophic failures are minimal for ultra-capacitors when compared to batteries in battery packs. The nature of battery packs suggests that neglect leads to deterioration and poor performance. With careful cable routing, ventilation, and fuse protection, an ultra-capacitor short circuit discharge during an accident can be isolated from vehicle occupants safely. A series parallel connection scheme also keeps the maximum voltage for each location at a safe level. The preferred capacitor module voltage is 200 volts. As the packs are made in module form, it allows for systems voltage to be set at 200, 400, 600, and 800 volts. The high voltage inner connections for the higher voltage can be made in a carefully positioned electrical distribution box with short leads to the traction drive. Such planning limits potential exposure to the high power sections of the electrical power transmission.

Capacitor Discharge-Another safety consideration is the advantage of the ultra capacitor over batteries to be discharged into a low Power State when vehicle service is needed. A simple resistive discharge circuit can accomplish this in a fairly short time period. Where batteries are concentrated into packs the chance for single module isolation is difficult. Completely discharging a pack is neither recommended nor practical and can be considered deleterious to the batteries.

Traction Drive-The traction drive developed from the HETB is optimized for a capacitor-based hybrid. The preferred configuration consists of one or more liquid cooled 3 phase induction motors. These motors are pre-engineered to be coupled directly into a power matched gear reducer or multi speed power shift transmission depending on the requirements of the application. The motor/gearbox design lends itself to parallel and series hybrids of the tee and wye pusher-types and vehicles with conventional front engine design.

Traction Motor-The rugged, totally enclosed, high efficiency, 3-phase induction design keeps costs down and dependability high. The totally enclosed liquid cooled design allows the vehicle designer to place the motor in the hottest, dirtiest environment without concern for providing clean cooling air or frequent maintenance. The motor can develop its rated torque continuously as coolant is flowing, even when stalled. There is no duty cycle reduction as with many air-cooled traction motors. Four frame sizes, with rated continuous power between 50 and 300 horses have been designed. This unique liquid cooled motor can be made available in other power ratings and frame sizes for design flexibility. When optimized for ultra-capacitor-based hybrids the motor must be designed to develop its rated power at the low voltage set point of the drive.

Gearbox/Transmission-The power matched gearbox optimizes motor size, efficiency, and cost. To accomplish the same performance without gear reduction, the motor would increase in complexity, weight, size and cost. Zierhut reinforced the benefit of multi-speed transmissions used with induction motors. He stated that "the best way to provide power down to very low speeds is with a gearbox that allows the motor to turn at high speed and then reduce the speed with a selected gear" [5]. He indicated that a multi-speed transmission gives a 4 : 1 improvement over other extended power range schemes like wye-delta change on the fly switching. The overall numerical gear ratio is selected to produce speed and torque peaks similar to diesel automatic drives, so gearing in the differential can remain unaffected.

The gearbox output shaft can be flanged to allow coupling to a conventional drive shaft or direct coupled to a transmission PTO. This may be an SAE type of flange or a NEMA type C face. System software insures smooth shifting and reduces shock loading. Integrating the motor/ gearbox into a vehicle is more manageable when flexibility is built into the design being considered.

Traction Controller-The traction controller for the HETB is an adaptation of proven industrial 3-phase IGBT based vector controller design. A simple six leg, three output inverter bridge configuration is utilized [6]. Zierhut stated that the delta-winding configurations produces a 73 percent increase in power range[5]. To take the full potential from this design, higher current rated IGBT power transistors are required in the inverter. Although they cost more, their physical size and weight is negligible. The overall weight and cost savings in the motor can easily justify the added transistor cost. Proprietary software and hardware changes in the controller insure smooth running at any speed.

For a dicussion of controller requirements for capacitor based hybrids see appendix 2.

In contrast to those used in a battery hybrid system, the components and control strategies of this system have been designed to allow for a wide fluctuation in voltage without performance loss or nuisance trip outs. The system is designed to optimize primary power unit/auxiliary power unit (PPU/APU) performance with the least amount of capacitor bank requirement. The system does not require any device between the inverter drive and capacitor bank.

ENGINE-DOMINATED CAPACITOR ASSIST PARALLEL BOOSTER DRIVES

Initially, parallel drives will be described. Then the booster driving of a parallel system will be explained. The components employed in the parallel system will be detailed and, finally, typical booster driven parallel drive applications will be developed.

PARALLEL DRIVE

The parallel drive is by design a simpler drive than a series drive is in hybrid design configurations. In this system a gasoline, diesel engine or gas turbine is the prime mover. Compared to traditional drives it is of a lower horsepower rating than what has been used traditionally. The prime mover in this case is coupled directly with the output in this case usually through a gear box or transmission. In the parallel drive, saprophytic loads such as air conditioning and power steering are also coupled to the prime mover directly.

<u>Booster Drive</u>-An electric motor which has the capability to act as an alternator also is incorporated into the system. This ultimately balances the load being applied to the prime mover. In the even of braking it serves as a power generator or alternator. In the event of encountering load resistance it acts as a booster electric motor adding energy to the prime mover which is typically the engine. During periods of idling or low loading the motor acts as an alternator and delivers charge to the ultra-capacitors and/or battery packs.

The parallel booster drive is designed to optimize the primary power and auxiliary power unit (PPU/APU) with the least amount of power requirement as possible. In the parallel form, the major components can be retrofitted to existing vehicles. This system does not require any device between the inverter drive and the capacitor bank. For market identity reasons the system has been named, *"Engine-dominated, Capacitor Assist, Hybrid Drive."*

PARALLEL SYSTEM HARDWARE

The parallel or *engine-dominated* system consists of a traction motor, inverter, capacitor banks, and transmission. These will be discussed as they can integrate into a modularized power package for a variety of different vehicle configurations.

<u>Traction Motor</u>-One or more low inductance traction motor(s) capable of delivering rated torque and power at the low voltage set point. The motor(s) is/are coupled to the mechanical power train

via a torque shaft which is either a live power takeoff from a traditional transmission or to the back output shaft from a front tandem drive axle or through a separate drive axle. During braking or cruising, the motor(s) will become a generator to charge the capacitors. The hybrid parallel motor is typically sized smaller in output than the motor sized for a series drive since it does not have to provide all of the traction effort.

Power Inverter-One or more inverter(s) capable of delivering rated power to the motor at the low voltage set point. Components sized to operate at the high voltage set point. Controls set up to eliminate instability at high voltage when using a low inductance motor.

Ultra-capacitor Banks-One or more capacitor bank(s) sized to deliver above or average traction power for accelerating the vehicle to rated speed. The capacitor bank has the capability to capture regenerative energy during braking. Batteries may or may not be used to supplement the ultra-capacitors depending on the application.

Transmission-Power for the vehicle can be delivered from a conventional engine with otto cycle or diesel being typical. The engine or motor is coupled to the driving axles through an automatic transmission of which several speeds are used. The engine is coupled to the transmission with a torque convertor of the *lock up* variety. An electronic controller to maximize efficiency and keep air pollutants low controls the engine. Auxiliary loads such as air conditioning and power brakes are coupled directly to the engine. The gear ratios employed within the transmission are selected to meet the vehicle's design requirements in terms of load in an efficient manner.

APPLICATIONS FOR PARALLEL HYBRID VEHICLES

This is more of a booster drive in terms of practical applications. This allows the use of minimum drive engine in the system and an electric motor that complements the engine when need arises.

Going up a hill, the stored energy in batteries or ultra-capacitors can be used to add to the existing drive engine.

The electric motor with its 3 phase design is turned into an alternator when the need arises. Upon braking the motor is switched to an alternator for regenerative braking. Also, while idling the motor may be switched alternator use depending upon the application. The engine may be called on to deliver 100% of the peak power requirement from time-to-time, as when climbing a hill. Even though instantaneous fuel mileage amy suffer in this process the overall mileage will be higher due to the overall higher level of fuel efficiency. This expalins how the ultra-capcaitors weight and vehicle volume comsumption can be economically justified.

Since the peak power requirement is a small part of the engine duty cycle, lighter *automotive* engines can be used in place of traditional heavy duty engines. The booster type of hybrid drive is ideally suited for applications in light duty buses, shuttles, light passenger vehicles, and delivery trucks of any size.

ENGINE DOMINATED CAPACITOR ASSIST SERIES DRIVE VEHICLE CONFIGURATIONS

Initially, series drives will be differentiated from parallel drive hybrid vehicle configurations. Then contemporary series vehicle configurations will be developed and projections for future series hybrid vehicle developments will be discussed.

Series Drives Described-The series hybrid drive is more complicated than the parallel drive hybrid vehicle configuration. The series drive integrates the three module; capacitor, traction drive, and controller into their next logical configuration by the addition of a primary power module (PPU) and an auxiliary drive unit. This configuration is more complicated than the booster drive in that it offers the additional benefit of added fuel economy in city loop transit applications.

The series drive is really an electric motor powered vehicle. The electric power is generated typically by and engine in the PPU. This electrical power is supplemented in time of need, as in going up a hill, by the batteries and or ultra-capacitors. In times of excess power as in braking or in going down hill the extra power generated by the PPU is stored in the electrical storage device or devices.

For market identiy reasons this system has been named, *"Engine-dominated, Capacitor Assisted, Series, Hybrid Drive."*

ENGINE-DOMINATED, CAPACITOR ASSISTED, SERIES, HYBRID DRIVE

The series configuration includes a primary power unit (PPU), an auxiliary power unit (APU), traction motor(s), engine controller, battery storage, and ultra-capacitor banks. These will be detailed as they apply to series hybrid vehicle configurations.

The Primary Power Unit (PPU)-The PPU size is reduced here for battery-based energy storage units and correspondingly larger units are required when ultra-capacitors-based storage units are used in place of batteries. The engine size reduction is developed as the vehicle load is balanced by the charging of the energy storage units in time of low load and discharging the energy storage units in time of high load.

The Auxiliary Power Unit (APU)-Often an APU employs an auxiliary electric motor to operate the saprophytic loads as in power steering and air conditioning. Sometimes the APU employs a single auxiliary motor while other plans use multiple auxiliary motors for these purposes. Multiple motors give loctional flexibility in the APU.

Traction Motor(s)-The traction motor, or motors, is fitted to a multi-speed transmission which allows the reduction in electric motor size and assures that the vehicle can handle the extra loads required for break away acceleration. The wheels can be connected directly to a wheel hub reducer or to a conventional differential depending on the specific application. The electric traction motor needs to be large enough to drive the bus in any drive cycle conditions. Another way of looking at this is that if a 250 HP Diesel is required for traction in an application, the electrical equivalent of that 250 HP diesel is the needed design requirement.

Engine Controller-A computer-based engine controller is needed to supply and regulate the power to the drive wheels. This system needs to have the capability of turning the traction motor into an alternator during stopping in the form of regenerative braking to turn the energy normally dispelled during stopping into recaptured electrical energy in ultr-capacitors and/or lead acid batteries.

Lead Acid Batteries and Battery Bank-Batteries are needed for the storage of electricity in some applications. They have the benefit of being capable of being charged while the vehicle is in storage. An example of this would be a parked bus in a bus garage charging like a forklift in an industrial plant. Batteries may be used in combination with ultra-capacitors or in lieu of them. The batteries are often packaged in battery banks for easier integration into a wide variety of vehicles and for specific application needs.

Ultra-capacitors-Ultra-capacitors may be used for more instantaneous charge and discharge. Due to their high farad ratings they have the ability to take on a charge very quickly and efficiently. They also can deliver that charge very quickly when compared to traditional lead acid batteries.

GAS TURBINE-DRIVEN ALTERNATOR-BASED SERIES HYBRID CONFIGURATIONS

The micro turbine offers a very efficient and lighter weight power source that has great potential to replace conventional engine PPU's [10]. Because they operate at high speeds, the series electric hybrid configuration a way to utilize the micro gas turbine in one of the simpler configurations. The gas turbine drives an alternator in place of a gasoline or diesel engine or other prime mover in the series hybrid vehicle configuration. Due to this simplicity of design it will likely be used in future production vehicles, at least initially. The integration of ultra-capacitors in place of batteries into these series configurations will make them cost effective.

FUEL CELL IMPLICATIONS

As fuel cell technology develops further and becomes cost competitive with gas turbines, diesel engines, and otto cycle engines they may be dropped into the place of the prime mover and alternator parts of the series hybrid vehcile configurations.

Applications for Series Hybrid Electric Vehicles-The gas turbine alternator-base series hybrid vehicles have applications in start and stop applications. An urban bus route would be particularly well suited for series hybrid applications.

The applications of series hybrid drive vehicles are more futuristic than the parallel hybrid drives at this time. They will work with otto cycle or diesel power plants that are available now. Series hybrid drives will be able to become more realistic as small turbine engines are developed and as the progress on fuel cells moves along.

CONCLUSIONS

Both parallel and series hybrid versions of the engine dominated computer assisted type are available to the vehicle designer today. As fuel prices soar and air pollution regulations become more stringent they show promise that is exponential. The series hybrid configuration has particular importance for cyclical route as in urban bus applications and for harnessing advanced PPU's as turbine driven systems and fuel cells become available. Parallel or *engine dominated capacitor assist booster drives* have potential for yielding greater return on investment in the short term.

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8. Hybrid Power Systems, Toledo, Ohio

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Appendix 1

Analysis of Ultra-capacitor Utilization in Hybrid Electric Vehicle Design

An analysis of information provided by Lev [1] and Mosely [2] provided the following insight into capacitor storage effectiveness over batteries for hybrid vehicles:

1. Capacitors are more efficient as storage devices than batteries. Water electrolyte/carbon ultra-capacitors have a charge to discharge efficiency of 97% - - the highest value of any commercially available electrical storage component. Battery efficiency seldom exceeds 65% even when operating in Partial State of discharge (PSoC) mode. Storage system efficiency reduces the energy storage potential.
2. Capacitors can safely go through 100,000 complete charge/discharge cycles whereas the best lead acid batteries can endure only 800 full discharge cycles. Even at 5500 cycles for PSoC mode, the ultra capacitor will last 18 times longer.
3. Power management and electronic controls for capacitors are much simpler than for batteries. Capacitor State of charge is based on voltage, which can be easily determined. Sealed battery State of charge needs to be estimated.
4. Capacitors do not need thermal management. Battery performance is enhanced with thermal management.
5. Capacitors are sealed and robustly constructed to make them suitable for installation within the vehicle's chassis. This keeps a low center of gravity. In some installations as much as 4000 LBS. of lead acid batteries have been located within the roof super structure.
6. Capacitors require no maintenance during their usable life [1].

One disadvantage of ultra-capacitors is that they have less energy density per pound when compared to the traditional lead acid batteries. For ultra-capacitor hybrids to succeed, the vehicle and hybrid drive must:

1. Be as light as possible to allow the maximum capacitor weight without exceeding vehicle GVW.
2. Engineered to extract as much energy as practical from the capacitors
3. Provide an adequate payback for the added cost for the capacitors can be achieved.

A further analysis of this data provided by Palumbo and Waggoner [3] indicated that:

1. Capacitors are 30% more efficient than batteries. Subsequently, battery pack capacity can be 30 percent smaller and in combination with capacitors the combined performance can be as high a traditional *larger and heavier* battery pack alone.
2. Capacitors costing 18 times more than comparable battery sets will be cost effective when battery replacement costs and performance differences are factored in. In terms of weight, ultra-capacitors can weigh up to 18 times more for the same dollar amount and be a viable energy management solution--*providing that the vehicle can carry the additional weight over batteries.*
3. To provide the same energy storage as ultra-capacitors, more battery weight is required due to their Partial State of Discharge mode operation (PSoC) than for the depletion mode operation of ultra-capacitor-based systems. Most modern battery hybrids utilize the PSoC mode and ultra-capacitor hybrids are depletion mode-based.

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Appendix 2

Controllers used in Capacitor-based Hybrids

The controller for a capacitor hybrid is designed to [1]:

1. Provide rated power in motoring and regenerating modes.
2. Accept wide range of input voltage without under and over voltage faults.
3. Operate in closed loop vector torque control mode to insure derivability and smooth performance.
4. Provide an interface to driver control inputs including a digital input for forward, off, and reverse.
5. Provide analog inputs for accelerating torque and decelerating torque commands.
6. Provide an analog output for tachometer.
7. Provide sequence outputs to automatically shift the transmission.
8. Be as small and as light as possible.
9. Operate in high impact and vibration environments
10. Operate in extreme temperature and humidity conditions.

Improvements included in the production version include:

1. A laminated electric buss to reduce weights and lower switching losses.
2. A liquid cooled heat sink to reduce size and operate in harsher environments.
3. An option of either 400v or 800 volt versions.
4. Optimized power components that tolerate greater high and low voltage conditions and produce rated outputs at a lower voltage to optimize capacitor size.
5. The controller integration into the application is made easy due to modular design and gives the vehicle designer a wide range of power ratings in a similar foot print.
6. The liquid cooled sealed design allows the controller to be placed in remote locations that optimize wiring and safety.

7. Controls set up to eliminate instability at high voltage when using a low voltage inductance motor.

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