ELECTRIC TRACTION DRIVES FOR HEAVY URBAN TRANSIT BUSES

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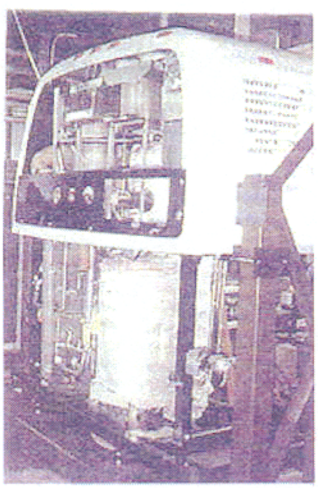
CLEAN, QUIET TRANSIT BUSES ARE HERE TODAY

A Federal Transit Administration Project



Abstract- *Environmental constraints are forcing major changes in the urban transit bus industry. Concerns with air quality in major US cities have forced transit operators to seek alternatives to standard diesel Internal Combustion Engine (ICE) propulsion. The near term solution has been to use Compressed Natural Gas (CNG) ICEs. However, these vehicles require infrastructure modifications to existing bus facilities, suffer from reduced operating range, and require a more extensive fueling facility due to the use of a gaseous fuel. This has led to a growing interest for electric drive technology as an alternate clean propulsion technology for urban transit buses.*

Hybrid-electric transit buses are now entering the transit bus marketplace. These electric vehicles allow the ICE to be optimally tuned to maximize efficiency and reduce emissions while traction batteries provide the capability to capture braking energy. New York City has recently placed a second order for hybrid-electric transit buses with the combined number now on order at 325. Fuel Cell technology is rapidly advancing which could accelerate the demand for electric drive systems.

Transit buses typically draw from the trucking industry for major components such as ICEs, axles, and transmissions. The preponderance of these vehicles are 40-foot buses with a maximum Gross Vehicle Weight of 39,500 pounds. Inner city bus routes entail low speed with numerous starts and stops. While bus weight and route profile dictate overall torque and power requirements, many other factors constrain the electric drive configuration. Determination of torque and power must take into account gearbox and axle ratios, component efficiencies, motor speed, and respective losses in the drive train. The traction motor must be bi-directional to recover or dissipate braking energy. The bus voltage may be established by the current limits on the switching electronics in the power management subsystem. Finally, adequate heat rejection must be provided. This paper addresses the issues impacting transit bus electric traction drives and describes some of the systems currently in use.

I. INTRODUCTION

We are sitting at the dawn of a true revolution in automotive propulsion technology and may be witnessing the twilight of the dominance of the ICE. These are no longer just the heartfelt beliefs of the true believers, pragmatic automobile manufacturers and business leaders are starting to realize that electric vehicles have long desired attributes and the technology and economics now favor true market entry. The environmental and efficiency advantages of electric propulsion and Fuel Cells have been long understood and accepted. Now there is a growing realization that the performance, infrastructure and cost barriers are not insurmountable. Hybrid-electric automobiles are now being offered commercially while almost every major automobile manufacturer in the world has stated an intention to introduce Fuel Cell powered automobiles.

Concurrently, there have been advancements in related engineering fields that will also hasten market introduction. Electric drive trains are now being introduced that will meet the automotive industry requirements. There has been a rapid growth in the number of companies entering this potential market. In the heavy-duty arena, hybrid-electric vehicles are starting to enter the transit bus marketplace with technology to meet the stringent environmental demands being placed on that application. Power electronics have reached the stage to make these developments possible while traction motors are becoming smaller and more reliable with improved efficiency. This industry is poised to satisfy the emerging electric vehicle market.

Transit buses offer a convenient and synergistic path to the introduction of electric propulsion for automobiles. These buses operate in the harsh inner city environment where reduced emissions can have direct and immediate impact on the quality of life of a large segment of the population. Electric vehicles are clean; urban air quality can be quickly and significantly improved by operating non-polluting transit buses. These buses will introduce the American public to the real advantages of the technology and further the goal of bringing electric drive technology into the marketplace.

Transit buses have unique operating characteristics and constraints that drive the design of the electric drive system. This paper identifies some of the key considerations to achieve acceptable designs and discusses the salient factors of different types of traction motors for the urban transit bus application.

II. TRANSIT BUS ELECTRIC POWERSYSTEMS

There are two promising technologies that can power commercially viable electric transit buses; hybrid-electric drives and Fuel Cells. A hybrid-electric vehicle combines two energy sources to produce traction drive power. Typically, the primary energy source (prime mover) is an ICE although it could also be a Fuel Cell. The supplemental energy source is an electric storage device (e.g., traction battery, ultra-capacitor, or flywheel) which also allows capture of some of the kinetic energy of the vehicle through regenerative braking. Regenerative braking is highly beneficial to an urban transit bus. The drive cycles of these heavy vehicles require numerous starts and stops. There is a lot of kinetic energy available to be recaptured and the regenerative braking significantly extends the life of the friction brakes.

Hybrid-electric vehicles may incorporate either a "series" or "parallel" architecture. Hybrid-electric vehicles employing a "series" architecture provide only electric power to the wheels. The two electric power sources are connected in series necessitating a voltage-matching converter to provide a single voltage/current profile to the traction motor controller. "Parallel" hybrid-electric vehicles use both energy sources to directly provide mechanical drive power to the wheels. One mechanical power path is directly from the ICE through a transmission/gear box, and the other from the energy storage device to an electric traction motor. This requires special attention to ensure smooth blending of the two mechanical devices into the drive axle. It should be noted that a "parallel" series architecture can not be accommodated if a Fuel Cell is used as the prime mover instead of a torque-producing device such as an ICE.

A Fuel Cell is an electrochemical device that produces electricity by reacting hydrogen and oxygen in the presence of a catalyst. The byproduct of this reaction is water (H_2O). Hydrogen may be supplied directly from on-board hydrogen storage (pressurized tanks, hydrides, or cryogenic liquid) or reformed on-board the vehicle from a liquid fuel source. The Fuel Cell produces electricity without using moving parts. It cleanly, quietly and efficiently converts the stored chemical energy of its fuel into electrical energy thus making it an excellent power source for transportation applications.

The Fuel Cell has emerged as a strong candidate to power future electric vehicles. This technology has proven to be an excellent producer of electrical power in a variety of applications and can derive its energy in the same way that a diesel or gasoline engine does, from a refillable liquid fuel tank. The Fuel Cell power plant for transportation can operate on non-petroleum liquid fuels, which could significantly reduce this nation's dependence on oil imports. Additionally it has emission levels well below any projected clean air standards. The Fuel Cell is quiet, clean, more efficient than internal combustion engines, and should require much less maintenance. Figure A. is a 100 kW Fuel Cell power plant (including on-board fuel processor) sitting in front of the rear section of a transit bus.

III. ELECTRIC DRIVE DESIGN PROCESS

Over 90% of the urban transit buses in this country are 40-foot vehicles. There is a growing market for cleaner vehicles (Compressed Natural Gas (CNG) or electric drive) driven by air quality concerns in our inner cities. There is a concerted effort to make these buses lighter to preserve roadways and bridges. There is a trend towards low-floor vehicles to reduce dwell time at passenger stops and to eliminate the electric wheelchair lifts. These developments impact the design of the vehicle drive train since weight constraints must be considered and the under-floor space claim is severely impacted by the low-floor coaches.

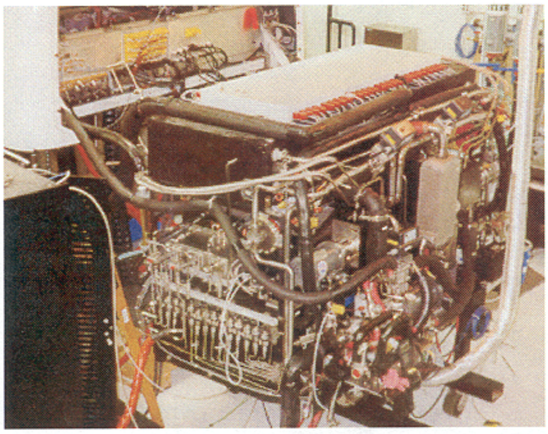


Figure A. 100 kW Proton Exchange Membrane Fuel Cell Transit Bus Power Plant

It is always desirable to develop the lightest, smallest, most efficient, and least expensive electric drive system possible. However, these goals cannot be satisfied in a vacuum. To properly design the electric drive system for an urban transit bus, it is critical to understand the desired bus physical characteristics, the drive cycle of the application, the vehicle constraints, and the technical limitations of the applicable hardware being considered. Two typical drive cycles (Arterial Route and Central Business District) are shown in Figure B. Transit routes are characterized by low-speed operation and numerous start stop cycles.

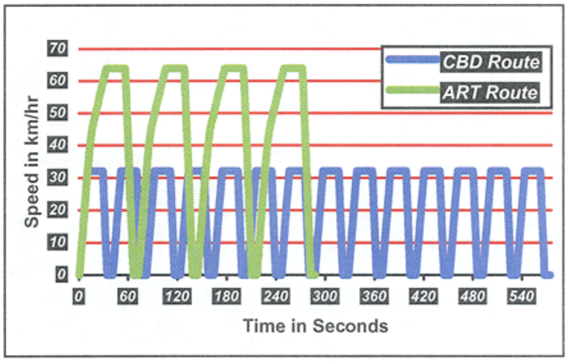


Figure B. Standard Transit Bus Route Profiles

Transit bus propulsion is determined by the vehicle weight, drag loads, and performance requirements as defined the Federal Transit Administration (FTA) "White Book." The White Book requirements of acceleration and gradability (Table A) must be met at the bus Seated Load Weight (SLW). SLW is the vehicle curb weight (empty) plus the weight of the same number of passengers as available seats on the bus. Weight per passenger is assumed to be 150 pounds. If a bus had a curb weight of 28,000 pounds and was designed to seat 40 passengers, the SLW would then be 34,000 pounds. White Book requirements would have to be satisfied at that weight.

Table. A. White Book Acceleration and Gradability Requirements

Acceleration			Gradability	
Time to Speed (seconds)	**Speed (mph)**		**Speed (mph)**	**Grade (%)**
5.6	10		7	16
10.1	20		44	2.5
19.0	30			
34.0	40			
60.0	50			

The drive train must match the traction motor speed to the vehicle speed while providing the torque multiplication necessary to produce the desired torque at the tire. The gear ratio of a single reduction transit bus rear axle can vary from approximately 3.4 to 7.4. This is typical of those found on single axle transit buses although higher ratio double reduction axles are available. The diameter of a rear wheel on a standard 40-foot transit bus is approximately 40.5 inches. Thus, to achieve a bus top speed of 60 mph, the input rotational speed to the axle differential for a single reduction axle would range from 1700 rpm to 3700 rpm.

System modeling is used to determine the necessary combination of torque and power at the bus wheel to meet or exceed White Book requirements. Vehicle weight, route grades, desired acceleration and top speed are inputs to this analysis. Acceleration power, air drag, rolling resistance, gear losses are also taken into account. Once the necessary combination of torque and power at the wheels is ascertained (taking into account efficiency losses in the gearbox and axle), a classic motor speed/torque curve is then used to select a traction motor that will meet or exceed the defined performance. Here it is necessary to consider motor losses (electrical and mechanical), inverter losses and any dedicated gearbox loss to ensure that the traction motor selected can supply the required power and torque.

Figure C. is the resulting traction motor speed/torque requirement for a 36,000-pound (SLW) 40-foot urban transit bus with a rear axle ratio of 6.2. It should be noted that the motor does not have to meet the constant torque portion of the curve on a continuous basis. A transit bus requires the maximum constant torque for brief (less than five minutes) periods of acceleration. The electrical power required to drive the traction motor for this vehicle is 150 kW. This power requirement may dictate a high bus system voltage (≥ 600 volts) to meet the current constraints of currently available electrical switching devices in the motor inverter.

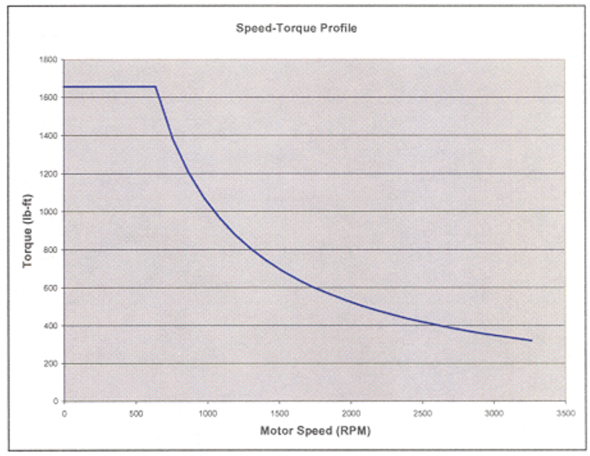


Figure C. 40 Foot Transit Bus Speed/Torque Curve

IV. TRACTION MOTOR DEVELOPMENT

Electric urban transit buses are reaching the commercial market. Many vendors have introduced electric motor products to satisfy that demand. Figure D. is the ArvinMeritor RE-17-345 Electric Drive Axle. This employs a helical/bevel double reduction axle with an integral 85 kW Siemans PV-5138 motor. The unit has a high-speed lubrication system (up to 9,000 rpm) and is used on the Mercedes "CITO" diesel electric Midi bus. These axles are in production for the European OEM market.

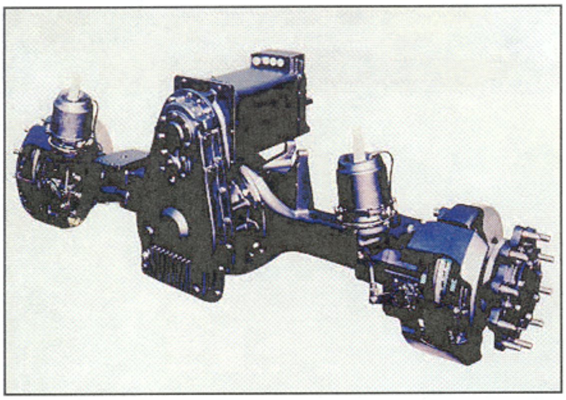


Figure D. ArvinMeritor RE-17-345 Electric Drive Axle

Figure E. shows an AC Traction Motor developed by BAE Systems. This unit interfaces with the BAE HybriDrive™ propulsion system and connects directly to a standard drive shaft to provide power and regenerative braking. It produces electric power of 186 kW continuous (238 kW peak) with an output speed into the driveline of 0-3200 rpm. This motor has been used on the two 40-foot Fuel Cell transit buses developed by the FTA and the hybrid-electric buses being developed for New York City.

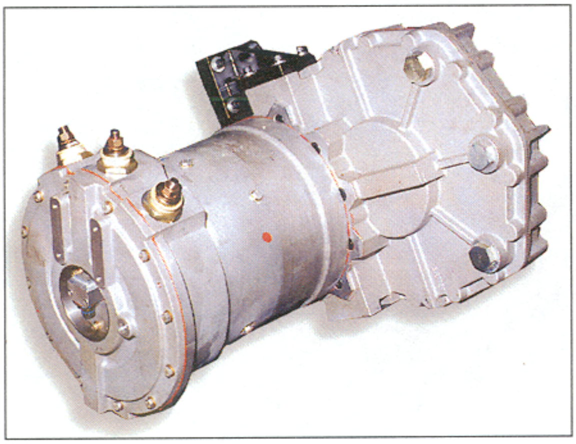


Figure E. BAE Systems A Traction Motor

Wheel motors offer another approach to satisfy the goal to commercialize low-floor, electric transit buses. The technical challenges include integrating the drive motor onto the hub while accommodating brakes and cooling in a tightly constrained volume. The bus designer must also account for the unsprung moment of these units in developing the bus suspension system. The wheel-hub drives transmit electric power directly to the respective wheels. One advantage may be to reduce the bus system voltage since the motor inverters need handle only half the traction power. This halves the current capacity of the power switching devices in each inverter. Figure F. is a wheel-hub drive employing an air-cooled, three-phase asynchronous motor. The unit was developed by ZF Friedrichshafen for DaimlerChrysler's NEBUS Fuel Cell test vehicle. Each wheel-hub motor has a peak output of 75 kW and a steady-state output of 50 kW.

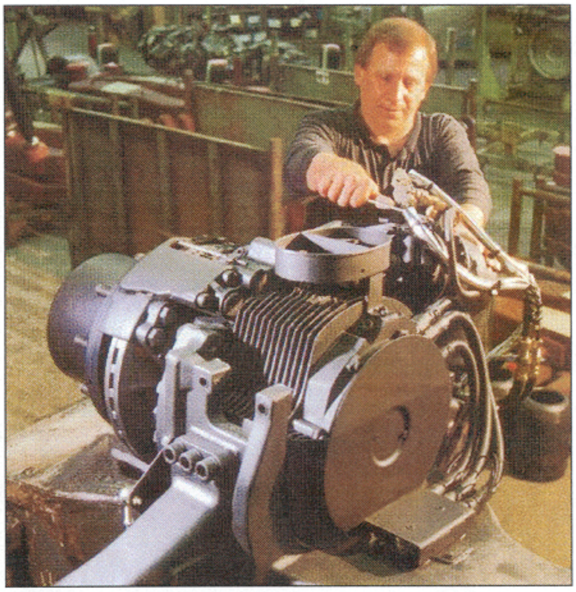


Figure F. NEBUS Wheel-hub Drive System

V. TRACTION MOTOR/DRIVE CHOICES

Back in 1900 there were only two basic types of electric motors: *DC Commutated and AC Induction.* The DC Commutated type motor was available as a shunt, series or compound connected machine. The AC Induction motor was manufactured with a squirrel cage rotor or wound rotor, which required slip rings for excitation. For most of the last century the DC motor series was the motor of choice for traction for most all electric vehicles such as railed vehicles and other types. The power source for these types of machines was usually DC from a power supply or from a battery source. One of the main features of the DC series machine for electric traction was the unique characteristic of its speed versus torque relationship. Most all traction applications require higher starting torque for accelerating the vehicle up to speed and low torque at a fairly high RPM's to maintain full vehicle speed. An Induction motor when powered by a 50 or 60 hz AC constant voltage source will not produce the required starting torque for vehicle traction. Therefore, the series motor was the motor of choice because of the speed versus torque relationship nearly exactly matched the requirements for vehicle traction applications.

Due to the obvious limitations of series wound DC motors such as efficiency and brush\commutator life, other motor choices must be considered for future traction applications such as the urban transit bus. Even though the Ward Leonard SCR drives significantly improved the performance and control of the series traction motors, the modern power electronic switches such as IGBTs and PWM mode control makes it possible to generate beautiful sine wave currents so that other motor types can be considered for vehicle traction. The three motor types which hold the most promise for selection as vehicle traction are flux vector controlled AC induction motors, permanent-magnet self-synchronous brushless and switched reluctance motors.

All three of these electric motor types and their respective inverter and control topologies are quite advanced in their development and thought to be suitable for vehicle traction. However, for traction usage, all three of these machines must be designed for very high power density. This requires some sort of forced cooling, usually water or oil. In addition, the phase windings must be wound with much more copper in the stator slots to reduce winding loses. Standard production slot filled percentages have historically been in the range of 30 to 40%. For high density liquid cooled machines the slot fills must be at least 70% with epoxy encapsulation to provide a thermal heat path to the cooling liquid via aluminum cooling jacket. In the case of the AC induction motors some sort of cooling is required for the rotor as well. Oil spray has been a common spray for these machines due to the difficulty in extracting heat from the rotating squirrel cage of the induction motor. Most of these induction motors have copper bared rotors rather than die cast aluminum to improve efficiency.

In the case of the permanent magnet self-synchronous machines, the rotor magnets are very expensive if the high density sintered grades of the rare earth magnets are used. It has been determined by enlarge that the bonded medium performance grade of neodymium iron magnets are the most cost effective for this type of machine.

The least mature of the three motor types is the switched reluctance or doubly salient poled motor. The rotor and stator are very simple to manufacture but low core loss thin laminations grades are required. In addition the firing angles for the phases require careful control for both turn on and torque relationship for vehicle traction but it tends to produce more audible noise and requires more careful and precise phase firing angles. Figure H-2 shows the typical SR inverter configuration for a three-phase machine.

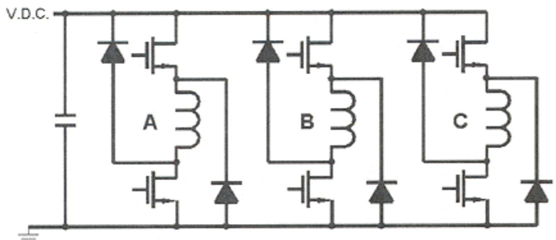


Figure H-2. Switched Reluctance inverter topology with two transistors and two diodes per phase

One of the important advantages of the SR motor is due to its speed vs torque relationship. At low RPM it produces very high starting torques. The SR machine can achieve very high speeds by advancing the phase firing angles. This allows the SR machine to be packaged with a much lower gear reduction than is required by either of the other two motor choices (particularly the AC induction).

In some instances it has proven to be very cost effective for the urban transit bus to keep the motor speed low for long bearing and gearbox life by using a standard automatic bus transmission made by companies such as Allison. Figure J shows a 250 KW AC induction motor made by Reuland Electric mounted to a dynamometer.

This is used with an Allison bus transmission by Xcellsis (a joint venture between Daimler Benz, Ford and Ballard). Figure K shows the inverter made by Saminco for the 250 KW traction motor for the Xcellsis fuel cell bus

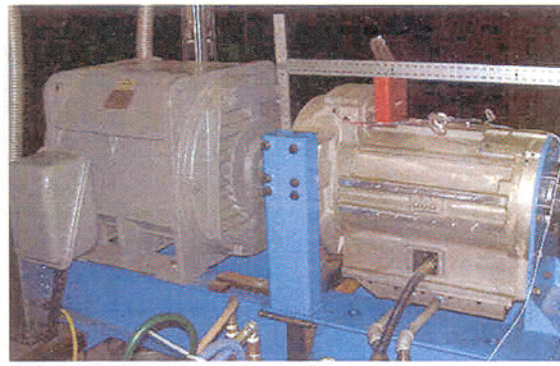


Figure J. 250 KW oil cooled Reuland AC Induction traction motor for fuel cell bus

Figure K. 250 KW inverter oiled inverter for 3 phase Reuland AC induction motor

Figures L describes a 70 KW PM Self-Synchronous motor integrated into a transaxle for fuel cell vehicles.

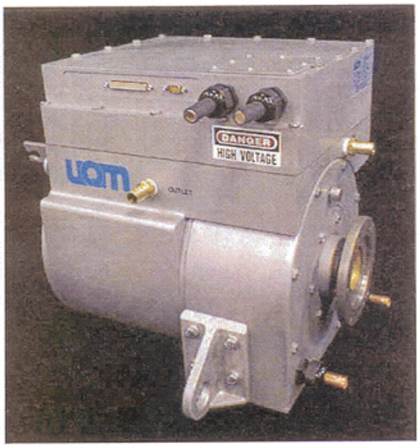


Figure L. 70 KW PM Brushless transaxle

Figure M shows the performance curves of this machine that is manufactured by UQM Technologies Inc.

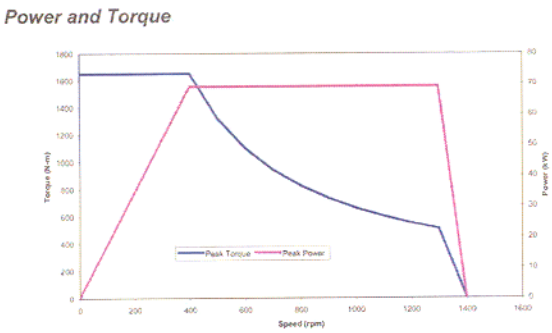


Figure M. Performance curves for 70 KW PM Brushless transaxle by UQM Tech.

VI. CONCLUSTION

The optimum choice for a traction drive system for urban transit buses is not clear-cut. Careful consideration must be given to the bus operating requirements and the features and cost issues of each motor and drive technologies. The selection of an induction motor system requires a large gear reduction with the motor operating at high speeds. If a PM self-synchronous drive system is selected the large gear reduction can be minimized if field weakening can be applied. It seems that the ideal traction motor would be the SR except it has problems with audible noise and arguable a more expensive inverter/control system. Most current bus traction programs use AC induction with increasing interest in PM self-synchronous. The future use of SR however is quite predictable and likely however, any of the choices are going to require some form of liquid cooling and high copper slot fills for the phase windings to maximize efficiency. The PM brushless has the problem of the high cost of permanent magnets and their retainment systems so that close attention will need to be paid to the market pricing of permanent magnets.

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