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Power sources for hybrid buses: comparative evaluation of the state of the art

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Abstract

Due to their beneficial effect on environment, electric vehicles are an important factor for the improvement of urban traffic and, more particularly, for a healthier living environment. A particularly promising field of application is the hybrid-electric city bus, which offers unprecedented opportunities for reducing energy consumption and emissions. Nowadays, various hybrid bus configurations are being proposed and are being demonstrated in several European cities with the support of the European Union's 'Thermie' programme. The most important hybrid bus project within Thermie is the Sagittaire project [EU Thermie Project Sagittaire, Newsletter 2, September 1998; EU Thremie project Sagittaire, unpublished documents], aiming to introduce hybrid buses in nine European cities: Luxembourg, Besançon, Alicante, Sintra, Stavanger, Trento, Savona, Athens and Bruges. © 1999 Elsevier Science S.A. All rights reserved.

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1. Hybrid structures for powering electric vehicles

The various possible power source configurations for hybrid vehicles can be differentiated into several categories, according to their structure and to their mode of operation [1,2].

One can consider the following.

1.1. Series hybrid vehicles

The series hybrid is a hybridisation of energy sources. In the series hybrid, the wheels are exclusively driven by one or more electric traction motors, the electricity being generated by an on-board energy source (diesel generator set, commonly called an auxiliary power unit-APU), with a traction battery acting as an energy buffer. The series hybrid is considered the most suitable solution for heavy-duty vehicles.

1.2. Parallel hybrid vehicles

On the other hand, the parallel hybrid is a hybridisation of drive systems. The wheels can be driven by either an electric motor or an internal combustion engine. This configuration is considered more adapted to light-duty vehicles.

1.3. Complex hybrids

These structures encompass three or more energy sources and/or drive systems. The possible options are manifold (series–parallel mixed structure, additional energy sources such as flywheels, capacitors, ...). An example of a complex hybrid is the Toyota Prius passenger car.

According to the mode of operation, one can consider the following.

1.4. Battery depleting hybrids

In this structure, the state of charge of the traction battery at the end of a service day is lower than at the beginning. The batteries thus have to be recharged from an external source (electricity grid).

1.5. Non-depleting hybrids

In a non-depleting hybrid, the state of charge of the traction battery at the end of a service day is equal to at the beginning. Only the APU provides energy to the vehicle. (The state of charge of the battery at any given time during service will of course be variable).

For use in heavy-duty vehicles such as buses, the series hybrid structure is generally preferred, since it allows one

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to benefit from the optimal traction characteristics of an electric motor on one hand, while optimising the operation of the combustion engine on the other hand. This allows for unprecedented low emissions and energy consumption.

Within the series hybrid configuration, different design philosophies are possible according to the relative power output of APU and battery. These move between two extremes: on one hand, the pure battery-electric vehicle (without APU); on the other hand, the diesel-electric vehicle (without battery).

This can be described with the aid of a parameter called the ‘hybridisation degree’, which represents the ratio between the continuous output power of the APU and the maximal power of the traction motor:

$$\rho_{\mathrm{hyb}} = \frac{P_{\mathrm{APU}}}{P_{\mathrm{mot}}} \tag{1}$$

It is zero for a battery–electric, and 100% for a diesel–electric.

The technical preference of discerning customers (as represented for example by the Sagittaire procurement group) clearly goes towards a low hybridisation degree, preferably lower than 50%. This represents a ‘small’ engine and generator set, which in itself would not be sufficient to deliver full traction power (e.g., for acceleration or hill climbing) to the motor, this peak power being delivered by the battery. During deceleration or standstill phases, the generator will then recharge the battery.

The advantage of such a configuration with a low degree of hybridisation is that the combustion engine can be tuned at an almost constant power level corresponding to its optimal operation point, leading to lower emissions and fuel consumption.

Configurations with large engines, corresponding more to a ‘diesel–electric’ drive train, will inevitably mean variable load conditions for the engine, leading to sub-optimal operation.

The choice for battery depleting or non-depleting vehicles is dependent on several operational considerations.

(a) If the vehicle is intended to be operated for a considerable part of its route in a pure electric (zero-emission) mode, battery depletion will be obvious. If a non-depleting vehicle is to be used in this operation mode, the hybridisation degree must be high enough to allow a sufficient APU output to recharge the battery.

(b) Battery depletion means that part of the energy is delivered to the vehicle from the electricity grid; this energy source may be preferred because it may be either more economic (for example if overnight recharging is used) or more environment-friendly than fossil or other fuels fed to the APU.

(c) Non-depleting operation does not require additional infrastructures, and offers the opportunity of transparent exploitation with traditional diesel buses.

2. Contemporary hybrid buses and their batteries

The choice of a suitable traction battery for a hybrid bus remains a very important issue. As one of the functions of the battery is to deliver peak power (during accelerations and hill climbing), the power density is a parameter of premier importance. Energy density however should also be considered, particularly for battery-depleting applications.

Several batteries are being considered by manufacturers today. The following table gives an overview of typical hybrid buses as presented by several leading European bus manufacturers participating in the tender the Sagittaire project.

All vehicles are series hybrids, and are classified in Table 1 by type of battery proposed. Let us now consider these vehicles, their batteries and the way the battery option reflects the design philosophy.

2.1. Options #1 and #2: the series hybrid with low hybridisation degree

The first two vehicles represent what can be called a ‘proven design’ in hybrid buses, in fact these vehicles (from the same manufacturer) are already being offered on a commercial basis, while all others are still to be considered prototypes. New body designs for these vehicles, encompassing integral low floors and the same hybrid drive technology, will be available during 1999.

These vehicles are primarily intended for non-depleting operation, although battery charging through an external source is possible. Their striking feature is the extremely low hybridisation degree, or in other words, the low output power of the generator. The engine powering the APU is

Table 1
Characteristics of hybrid buses

Bus	Length (m)	Tare (kg)	P_{mot} (kW)	P_{APU} (kW)	r_{hyb} (%)	Battery type	Battery (kg)	Battery (Ah)	Battery (V)
#1	12	13 150	164	36	22	Pb–acid	2250	100	600
#2	6	2690	32.5	12	37	Pb–acid	850	100	192
#3	10.3	8000	110	60	54	VRLA	800	85	324
#4	9	11 240	80	105	125	VRLA	1470	70	576
#5	12	11 650	150	80	53	Na/NiCl	840	240	284
#6	12	12 500	160	150	94	Ni/MH	530	60	350

in fact a 2.5 l for the 12-m long bus and a 1 l for the 6-m minibus; this size of engine is more readily associated with a passenger car than with a bus! The APU is tuned to work strictly at its constant power output, which allows the bus to move at a constant speed of about 35 km/h on the level. Extra power for acceleration or hill climbing is taken from the battery.

Tests performed by CITELEC [3] on a 12 metre vehicle of this type (albeit one fitted with a natural-gas powered APU) have shown that during a typical city bus exploitation cycle (measured on an actual Brussels city bus route), the battery state-of-charge remains constant from the beginning of the test to the end, highlighting the non-depleting character of the operation. The constant power mode of the APU allows for energy-efficient and environment-friendly operation: the tested vehicle showed emissions, but these fell within the standards for passenger cars!

In their present production version, these vehicles come with a conventional flooded lead–acid traction battery, with tubular positive plates. This battery type provides the most economical solution, whilst offering a power density which is sufficient to provide the vehicle with acceptable performance levels (comparable to a conventional diesel bus). Energy density of this battery allows a zero-emission range of at least 20 km. The drawback of the use of these batteries is of course their substantial weight (more than 2 tonnes of battery for the 12-m vehicle).

For this reason, these vehicles are now being fitted experimentally with alternative batteries. One of the operators using the 6-m vehicles is now experimenting with nickel/cadmium batteries. The results are very promising, due to the enhanced energy density compared to lead–acid, and also because of the excellent power density of these batteries; their cost is, however, substantially higher.

A separate Thermie programme activity is introducing advanced batteries into 6-m buses. The chosen battery type is the ‘Zebra’ sodium/nickel chloride high temperature battery. These vehicles will be commissioned early 1999 in Trento, Italy, and in Oxford, England.

2.2. Option #3: A design with advanced lead-acid batteries

Vehicle #3 is an innovative lightweight body design, for which a type of advanced lead–acid batteries have been selected. This maintenance-free battery consists of semi-bipolar plates made of woven lead wires. Although this battery offers very promising values of energy and power density, there are some considerations concerning its cycle life, particularly in a demanding application like a city bus.

2.3. Option #4: High hybridisation degree with VRLA batteries

Vehicle #4, a low-floor midibus, presents a high hybridisation degree, exceeding 100% (One reason for this is due to the rather modest motor power in this vehicle, which has in fact been designed for use in a flat country). The APU thus has surplus power. This is the result of a particular design philosophy aimed at a typical mode of exploitation. In fact, during ‘hybrid’ operation, all drive power is provided by the APU and the battery is never drained (although it is recharged during braking and by the APU), making the mode of operation actually diesel–electric. This allows the battery to be kept at maximum state of charge ready for zero-emission operation in city centres. On the suburban part of the route, the APU’s excess power allows it to recharge the battery for the next run through the city centre. This allows for extended zero-emission routes while operating in a non-depleting hybrid mode.

The batteries of this vehicle are valve-regulated lead–acid (VRLA) with gelled electrolyte, mounted on the roof of the vehicle. These batteries are maintenance-free and available at a reasonable cost; vehicle performance would however benefit if alkaline batteries could be used, but the cost would be substantially higher.

2.4. Option #5: A design with advanced high-temperature batteries

This vehicle presents an innovative, integral low body floor with a modular design, all traction equipment being located at the rear end of the bus.

The interesting feature of these buses is the choice of an advanced battery: the ‘Zebra’ sodium/nickel chloride high temperature battery. This is offering several interesting features for this application: high energy density and sufficient power density, also freedom of maintenance. The energy losses due to the high operating temperature of the battery, and the related self-discharge for maintaining the temperature during periods of inactivity are no problem for a city bus which is intended to be operated on a daily basis.

However, as of December 1998, the future prospects for production and commercialisation of the Zebra battery are unsure, due to a number of business reasons which go beyond the scope of this paper. The author regrets the fact that the battery might not be available for future use in hybrid (or battery–electric) buses, since it looks like one of the most promising designs for this application.

2.5. Option #6: A high degree of hybridisation: diesel-electric

The #6 vehicles are fitted with high-power APUs and are basically diesel–electric buses with an additional battery fitted to allow zero-emission operation. The high power of the APU will invariably lead to dynamic operation of the APU at different power outputs, leading to a lower energy efficiency and higher emissions compared with a constant-power APU. Notwithstanding the potential merit of diesel-electric drives (which still take advantage of the superior traction characteristics of the electric motor), these vehicles are not to be considered as real 'hybrid' buses.

The proposed batteries are of the nickel/metal hydride type, with excellent power density properties. Nevertheless, the extremely high cost proposed for these (pre-production) batteries and their sensitivity to high ambient temperatures are considered as serious drawbacks.

3. Battery overview and future tendencies

As can be seen above, various battery designs [4] are being considered for application in hybrid buses. The 'definitive' battery cannot be defined as such; however, following considerations can be made.

(a) Flooded lead–acid batteries represent a well-known and mature technology which continues to provide an economical solution despite its high weight which limits the zero-emission range.

(b) VRLA designs eliminate maintenance and may offer improved energy and power densities; their reliability and longevity (a premier issue for heavy-duty applications) are however dependent on strict battery management. Innovative cell designs will have to prove their value in this field.

(c) Alkaline batteries (nickel/cadmium or nickel/metalhydride) offer excellent performances, particularly in power density, which is very important for a hybrid vehicle. Their cost however is very high.

(d) Advanced batteries represent a very promising solution, combining several characteristics which suit this particular application. The 'Zebra' sodium/nickel chloride battery presents itself as a very interesting option which is worth being deployed in demonstration fleets.

(e) Other advanced batteries, such as lithium-based designs, have not yet reached the hybrid bus scene, but may become available in later years.

4. Conclusions

The hybrid city bus is to be considered one of the most promising fields of application of electric traction in road vehicles today. Whereas the series hybrid structure is universally chosen for bus applications, the choice between battery-depleting or non-depleting hybrids will depend primarily on exploitation constraints.

The 'ideal' battery for a hybrid bus is far from being available, as reflected by the wide array of battery types proposed by various manufacturers. For the strenuous operation of a city bus, not only power and energy density of the battery, but also reliability, longevity and cost are premier factors to be considered, offering a major challenge to battery manufacturers.

References

[1] EU Thermie Project Sagittaire, Newsletter 2, September 1998.
[2] Joseph Beretta, New classification of electric-thermal hybrid vehicles, EVS-15 Symposium, Brussels, 1998.
[3] European project APAS-TAUT-0007, Development of a natural gas-electric hybrid city bus with extra low emissions, ALTRA-TNO-CITELEC, 1997.
[4] D.A.J. Rand, R. Woods, R.M. Dell, Batteries for Electric Vehicles, Research Studies Press, 1998.