

Design of a Hybrid Power Plant for City Buses

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This paper presents a preliminary system design for a no-emission hybrid power plant for city buses working in a "dense grid" transportation network with short, regular stop spacing.

The vehicle is driven by two electric motors powered by a hybrid unit composed of a fuel cell and flywheel energy storage system that takes into account the characteristics of urban routes.

The advantages and disadvantages of flywheel technology on board a vehicle are examined and discussed and an in-depth study of the proposed hybrid architecture was performed by analyzing and measuring the main power components for a small sized city bus with a 15 passenger capacity.

Keywords: Buses, Public Transport, Fuel Cell vehicles, Flywheel

1. INTRODUCTION

Small city buses with a reduced capacity are an essential component of above ground urban transportation systems and more suitable in terms of efficiency. This is particularly true for systems consisting of a "dense grid" transportation network with short, regular stop spacing (300-500m), and segments covered by "shuttle-type" vehicles with high operating frequencies.

Previous studies have shown that buses with a capacity of between 10 and 50 passengers constitute about 70-80% of the entire fleet in "dense grid" network systems [1]. The environmental aspect of this assumes considerable importance in urban areas and hence the request for no-pollution vehicles. Currently, vehicles driven by electric motors that run using the power stored in batteries are the most common alternative to vehicles with an internal combustion engine.

However old batteries also represent a source of chemical pollution, in addition to the disadvantages associated with their use: low capacity, long recharging times, weight and short lifetimes.

Hydrogen based fuel cell (FC) vehicles, on the other hand, represent a more suitable alternative combining zero emissions with the efficiency of a vehicle power system. Many studies have in fact examined and proposed hybrid power configurations for zero pollution vehicles [2,3].

This paper examines a small sized city bus with electric traction powered by a hybrid unit made up of a FC and a Flywheel Energy Storage System (FESS) in the place of conventional chemical batteries.

2. HYBRID POWER PLANT

The term hybrid power is generally used to describe the energy generated by two or more different energetic units mounted on board.

Current thinking foresees two different ways of using FCs on board vehicles: FCs alone and a hybrid solution. In the former case a powerful FC system would be needed.

The second solution entails the use of a FC coupled to an energy storage system that provides electric power when the FC has insufficient power output, and stores surplus electric energy generated by the FC. In addition, when a FC is used in combination with batteries, it acts as a battery charger whilst the batteries take the heavy loads and let the FC operate more smoothly [4].

We propose a bus configuration that uses an electric traction motor powered by a hybrid power unit (HPU) consisting of a FC converting fuel (hydrogen stored in a vessel on board) into electricity connected to a FESS by a control system C.

The electric energy, converted from chemical energy in a FC, is used to power the traction motors (M_T) or is stored in the FESS when no traction power is required.

The FESS is an electro mechanic device consisting of, in schematic form, a flywheel (F), coupled on the same shaft to an electrical device used both as a motor (M_F) and electrical generator (G_F). The system releases its energy by using the momentum of the flywheel to power the generator G_F . Mechanical energy is stored by using the M_F to increase the speed of the spinning flywheel by accelerating a rotor and maintaining, in inertial kind, the energy in the system. Energy is stored and extracted by electrically controlling the speed of revolution.

The vehicle has two traction motors M_T each of which is directly coupled to the wheels by a reducer

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(R); the motors are fed by the HPU and by two suitable converter/control systems C_1 . The proposed traction motors could be brushless dc types with permanent magnets given the advantages that this type of motor offers: low noise, high efficiency, low maintenance and ease of control [4]; they can also operate as a generator (G_T) when the controller sets a negative speed for the machine.

A simplified scheme of the hybrid architecture proposed is shown in figure 1. Two reversible electric dc links connect the HPU to the traction motors turning the wheels and providing propulsion; hence the power path from engine to driven wheels is completely electrical.

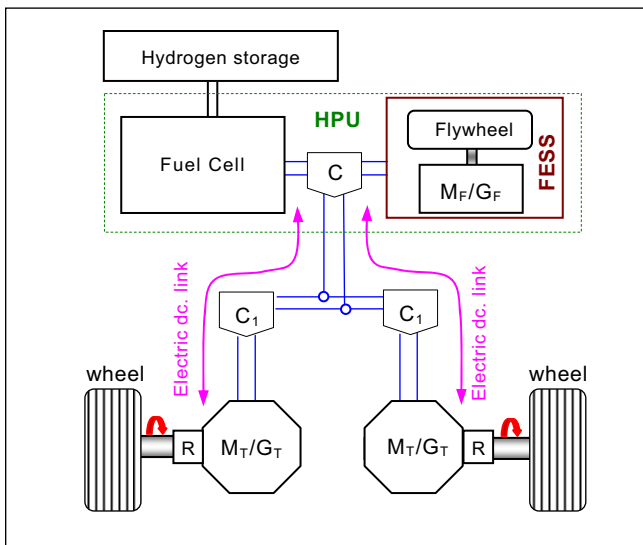


Fig. 1 Hybrid architecture scheme

The urban route implies cyclical and non-homogeneous motion in addition to phases of acceleration, steady motion, deceleration and stopping time, to allow passengers to get on and off.

The analysis of the power system has been correlated to the characteristics of a standard route cycle assuming that the vehicle uses bus lanes with regular, stop spacing.

The work principles of the proposed hybrid configuration in relation to the four phases of a standard cycle and their duration (end and start times), are:

1. Acceleration ($t_1 - t_0$): The vehicle accelerates and relies on the FC and the FESS to provide the necessary power. The mechanical energy previously stored in the flywheel is transformed by a generator G_F into electrical energy and then redistributed by the C and C_1 control systems to supply the traction motors M_T .
2. Steady motion ($t_2 - t_1$): The bus runs at constant speed; the traction motors M_T rely on the FC and, if necessary, the FESS;
3. Deceleration ($t_3 - t_2$): The bus runs with inertial motion or breaks. The FESS is used for storing regenerative braking energy captured by the

generator G_T when the vehicle decelerates. This is controlled by the C_1 and C systems

4. Stopping time ($t_4 - t_3$): The bus stops to allow passengers to get on and off; the energy supplied by the FC is stored in the FESS by control C. The electrical energy converted from chemical energy in the FC, is used to power the motor M_F which spins the flywheel at maximum rotational speed; thus the electrical energy is transformed and stored as mechanical energy.

During the route cycle, the electrical energy generated by the FC during phases 3 and 4 is stored as kinetic energy in the FESS and subsequently transformed back into electrical energy and redistributed to supply the traction motor when more power is needed (phases 1 and 2).

The energy E_T necessary to power the vehicle during a single route cycle, is calculated according to the following equation:

$$E_T = \int_{t_0}^{t_4} \frac{T(v) \cdot v \cdot dt}{\mu} \quad (1)$$

where $T(v)$ in kilograms is the traction thrust of the vehicle, dependent on speed (v) in metres per second, and μ is the electromechanical efficiency of the vehicle.

2.1 Flywheel technologies

Flywheels of various forms and dimensions have been used in industry for hundreds of years and iron, steel and composite flywheels are still used as energy storage devices.

Lead-acid battery technology is used for hybrid electric energy storage but it has poor energy density, limiting vehicle performance.

Ultracapacitors (supercapacitors) and flywheels represent more recent alternatives to battery.

Ultracapacitors have about one order of magnitude higher power and a much longer cycle life than batteries but they have much lower energy density. Capacitors on the other hand are a perfect storage solution below the 0.1 second range. Flywheels are efficient for a power to energy ratio of 1 second to 10 minutes whilst the battery ratio is in the order of 1 hour or greater [5]. The flywheel system is also more efficient in terms of energy capture and release from regenerative braking. There are significant advantages in using flywheel technology rather than batteries: the specific energy of a flywheel system is 5-10 times greater than that of an ordinary battery; flywheels are unaffected by the number of charge/discharge cycles, batteries on the other hand, have a typical life cycle of less than 1000 charge/discharge cycles. Flywheels are not as limited as batteries in the amount of energy they can hold; they are unaffected by temperature changes and do not suffer from memory effect. From an ecological point of view, flywheels are more environmentally-friendly being made of largely inert or benign materials.

A further advantage of flywheels is that by a simple measurement of the rotational speed it is possible to know the exact amount of energy stored.

The kinetic energy stored in a rotating flywheel increases linearly with mass and goes as the square of the rotational speed, as is highlighted by the equation:

$$K_E = \frac{1}{2} I \omega^2 = \frac{1}{2} k m r^2 \omega^2 \quad (2)$$

where ω is the rate of rotation in radians per second, I is the moment of inertia of the rotor about the center of rotation in squared kilogram-metres, m is the rotor mass in kilograms, r is the rotor radius and k is the inertial constant which is dependent on rotor shape.

Stress produced in the rim is proportional to the square of linear speed at the tip.

For a thin ring, the maximum hoop stress σ_s in N/m^2 is related to the specific energy (stored per unit mass) and density ρ of ring material in kg/m^3 according to the equation:

$$\sigma_{\max} = 2\rho \frac{K_E}{m} \quad (3)$$

So the best materials for flywheels are those with high specific strength $\sigma_{\max}/\rho$ which corresponds directly to specific energy K_E/m .

To optimize the energy-to-mass ratio, research today focuses on making flywheels spin as fast as possible and high strength, low density fibre filament rotors.

The use of massive flywheel accumulators is limited by the danger of explosive shattering of the wheel due to overload. Consequently, traditional (iron or steel) flywheel systems require strong containment vessels as a safety precaution which increases the total mass.

Recently a magnet array has been introduced, mounted on the inside face of the ring it interacts with the stator windings to make a motor/generator, which in turn is used to spin the ring up to store mechanical energy and to extract that energy by generating electricity [6]

Second generation flywheels, on the other hand, use high tensile strength, composite materials which can sustain the centripetal forces of very high speed revolutions. Carbon fiber rims have attained tip speeds in excess of 1000 meters per second; the rotor is suspended by magnetic bearings and housed in a vacuum chamber to minimize energy losses [7,8]. The round trip energy efficiency of modern flywheels can be as high as 90%.

The disadvantage of flywheel technology is that it is still in its infancy with respect to chemical batteries; consequently current costs are too high to make flywheels competitive in the market place. However, recent data looking at the efficiency and expected longevity of flywheels suggests they are highly competitive for applications with frequent charge-discharge cycles [9].

When kinetic technology is housed in running vehicles, flywheels also act as gyroscopes producing negative

effects on the vehicle's handling while turning. This problem can be attenuated by neutralizing the gyroscopic effect using an inertial device or counter-rotating pairs of separate flywheel systems.

3. SYSTEM DESIGN

In accordance with the characteristics of the vehicle and its operation within the urban network during a standard cycle time, the value of constant FC power is obtained using the equation:

$$P_{FC} = \frac{E_T}{t_4 - t_0} = \frac{1}{(t_4 - t_0)\mu} \int_{t_0}^{t_4} T(v) v dt \quad (4)$$

The components of the HPU are dimensioned by imposing an energetic balance between consumption and production.

For each route cycle, the consumption of energy required by the traction motors M_T (phases 1-2) must be equal to the sum of the energy emitted by the FC (phases 1-4) and the energy from any regenerative braking (phase 3). Hence:

$$\int_{t_0}^{t_1} P_T dt + \int_{t_1}^{t_2} P_T dt = \int_{t_0}^{t_4} P_{FC} dt + \int_{t_2}^{t_3} P_{GT} dt \quad (5)$$

where P_T is the electrical power required by the traction motor M_T and P_{GT} is the electrical power of the generator G_T .

The average power of the FESS motor M_F can be calculated using the equation:

$$P_{MF} = \frac{\int_{t_2}^{t_4} P_{FC} dt + \int_{t_2}^{t_3} P_{MG} dt}{(t_4 - t_2)\mu_f} \quad (6)$$

where μ_f represents the average efficiency of the FESS during both the storage phase and the energy emission phase.

The average power of the FESS generator G_F can be calculated according to the equation:

$$P_{GF} = \frac{\int_{t_0}^{t_2} P_{MT} dt - \int_{t_0}^{t_2} P_{FC} dt}{(t_2 - t_0)\mu_f} \quad (7)$$

In order to investigate the proposed hybrid architecture in more detail, a small city bus with a passenger capacity of 15 (total mass approximately 5800 kg) was considered and the main components of the power system, analyzed and measured in accordance with the characteristics of a standard route cycle.

It was assumed that the bus would run at a maximum speed of 33 km/h along flat bus lanes with average

stopping distances of 400m. The following assumptions were also made: a constant acceleration and deceleration of 0.55m/s^2 and 1.2 m/s^2 respectively, a stopping time of 30 seconds, FESS efficiency μ_e of 0.85, a cylindrical shaped flywheel (material density of 7800 kg/m^3) and rotation speed of between 5,000-15,000 rpm.

To err on the side of caution, energy from regenerative braking was omitted from our calculations.

Table 1: Main data concerning the hybrid power plant

		Unit	Value
FESS	Flywheel diameter	m	0.50
	Moment of inertia of rotor	kgm^2	0.37
	Mass of flywheel	kg	12
	Tensile stress	MN/m^2	530
	Peak power of motor M_F	kW	10
	Peak power of generator G_F	kW	40
FC	Power	kW	12
Traction Motors	Average power	kW	19
	Peak power	kW	52

Table 1 lists the design data of the main components of the hybrid power plant: FC power results at 12 kW and the peak power of each traction motor M_T , 26 kW. The data concerning the FESS reveal that when the rotor has a diameter of 0.50 m and mass of 12 kg, generator G_F power is much higher than motor M_F power. So FESS dimension must be related to the power requirements of its generator.

Using the formula (3) the maximum tensile stress in the rotor spinning at 15,000 rpm is about 600 (MN/m^2), which is about three times lower than the yield strengths of steel; so the rotor could also be constructed using traditional material.

The work principle of the hybrid power plant is shown in figures 2-7; curves are related to the differing phases of the route cycle which are identified by a circled number.

Figure 2 shows the speed of vehicle vs. time; in accordance with the project's parameters the vehicle starts at a constant speed, reaches maximum speed (9.2 m/s), decelerates and stops for 30 s to allow passengers to get on and off.

Figure 3 shows the power of traction motors M_T and FC vs. time; FC power is respectively 4.3 and 1.6 less than the maximum and average power of the traction motors M_T . This is obviously an advantage in terms of reducing the size, weight and costs of the FC.

Figure 4 shows the flywheel rotational speed vs. route time of vehicle.

When the vehicle accelerates (phase 1) and runs at steady (phase 2), the energy is drawn from the FESS by G_F and the rotating components slow down until $\omega_1=524\text{ rad/sec}$ (5,000 rpm). When the vehicle decelerates and is stopped, the FESS is electrically charged and M_F speeds up the flywheel until $\omega_1=1571$

rad/sec (15,000 rpm).

Figure 5 shows the kinetic energy of the flywheel vs. the vehicle's route time: the peak value of kinetic energy stored in the flywheel is 0.45 MJ.

Figures 6 and 7 show flywheel torque and flywheel power vs. vehicle route time.

In both cases, the route phases 1 and 2 imply negative values of torque and power because the FESS releases its energy by using the momentum of the flywheel to power the generator G_F ; phases 3 and 4 imply positive values as mechanical energy is stored by using the M_F to increase the speed of the spinning flywheel.

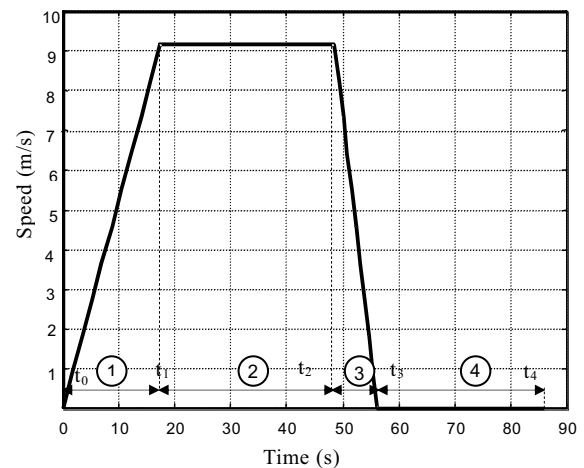


Fig. 2 Speed of vehicle vs. route time

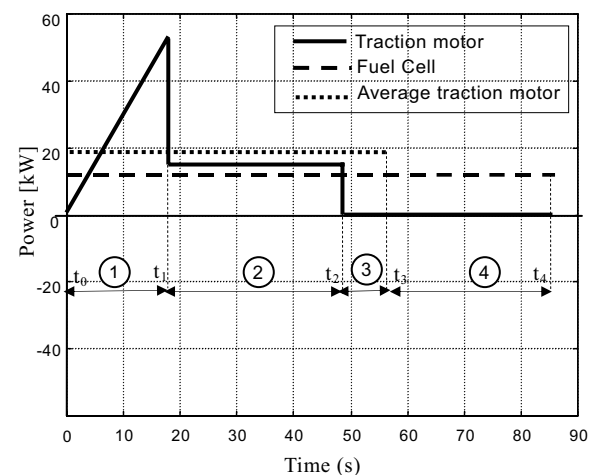


Fig. 3 Power vs. route time

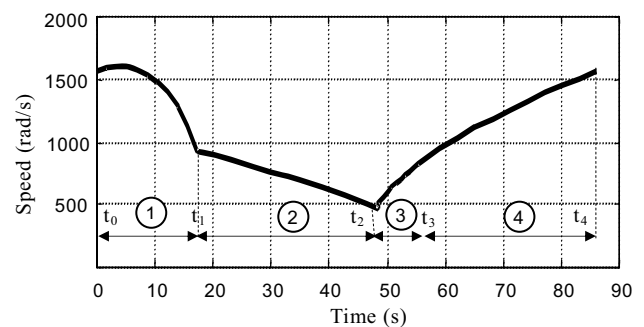


Fig. 4 Rotational speed of flywheel vs. time

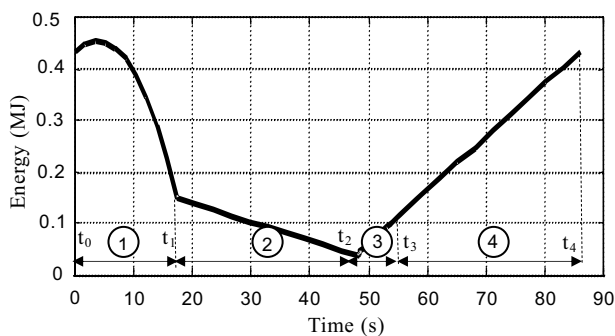


Fig. 5 Energy of flywheel vs. time

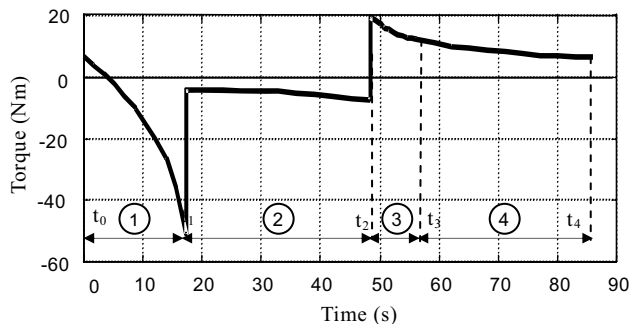


Fig. 6 Torque of flywheel vs. time

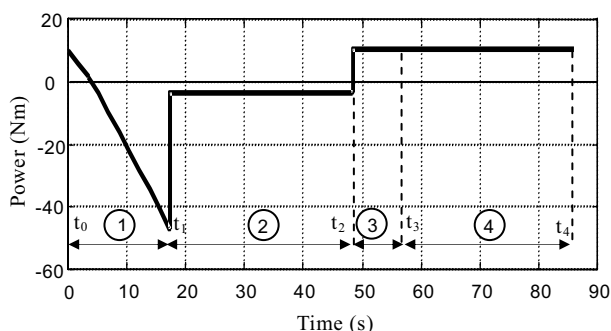


Fig. 7 Power of flywheel vs. route time

4. REGENERATIVE BRAKING

This section looks at the energy contribution from regenerative braking in accordance with the hypotheses used in the previous calculation.

The generator G_T allows the recapturing of a great part of the vehicle kinetic energy that otherwise would be lost to heat when braking; G_T uses torque to create electric energy that is successively stored in the FESS by increasing the flywheel rotational speed within the pre-fixed limits (5,000-15,000 rpm).

A G_T efficiency of 0.90 and FESS (charge-discharge) efficiency μ_c of 0.85 were assumed as was the fact that regenerative braking takes about 80% of the kinetic energy normally wasted during braking. Under these conditions, the energy from regenerative braking (0.128 MJ) yields about 14% of the energy necessary to power the vehicle during a single route cycle.

In the light of the results of the previous section, the computation of energy from regenerative braking in the system produces the following HPU variations:

- FC power decreases by about 13%;
- peak power of FESS generator M_F increases by about 5%;
- average energy of FESS flywheel increases by about 17%.

These results highlight how this regenerative braking system saves a great deal of energy when compared to a traditional vehicle with batteries.

Moreover the partial regeneration of kinetic energy allows for FC power approximately 5.2 times lower than the peak power of the traction motor, with the obvious advantages of reducing FC size, weight and costs. Lastly, our results indicate that the size of the FESS does not significantly increase and is related to the power requirements of its generator.

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BIOGRAPHY



Gino D'Ovidio was born in L'Aquila, Italy, in 1964. He graduated from the University of L'Aquila in civil engineering in 1991, and is presently an assistant professor in the Transportation Dept. of the Faculty of Engineering - University of L'Aquila where he teaches "Planning of Transportation Systems".

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