Conceptual Evaluation of a Fuel-Cell-Hybrid Powered Bus

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***Abstract* - This paper considers the conceptual design of a fuel-cell-hybrid engine to replace the conventional diesel internal combustion engine for use in London buses. Fuel cells are expensive power units costing in the region of £2.50/W compared to the conventional diesel-engine at 5p/W. A fuel-cell-hybrid solution is proposed to minimize initial costs whilst achieving good operational performance and specifically reducing greenhouse gas emissions for future 'zero-emission zones'. Different London bus types and their routes have been reviewed with route 226 (from Ealing Broadway Station to Golders Green Station) and the Alexander Dennis Enviro 200 Dart bus being selected for detailed study. Considering factors such as number of stops, route length, public demand, bus dimensions and weight a series fuel-cell-hybrid power plant using 20 kW polymer electrolyte membrane (PEM) fuel cells with a nano-phosphate Lithium-ion battery providing power to four AC three-phase induction propulsion motors is proposed. The fuel-cell-hybrid engine has been designed with re-engineering of the bus in mind to layout level and performance analysis has been undertaken using computer based simulation.**

***Keywords*—fuel cell, series hybrid bus, battery, power conditioning, converter, vehicle operating strategy**

I. INTRODUCTION

The fuel cell (FC) is a clean and efficient power unit that has undergone substantial development in recent times and is now commercially available offering a clean power source for transportation. Compared with the diesel internal combustion engine (ICE) the FC offers benefits of high efficiency and zero greenhouse gas emissions. The FC converts chemical energy directly into electricity without the need for combustion. The FC can use different kinds of fuels when using a reformer but the reaction of importance is between hydrogen (H_2) and oxygen (O_2) to form water and free electrons used for electrical power hence compressed H_2 as a fuel is usually preferred. FC have drawbacks such as low power density, are developing technology, currently have short lifetimes and are expensive costing around £2.5k per kW. However increasing pressure to curb emissions achieved through implementing 'Low Emission Zones' with increasingly stricter limits, then it would seem FC potentially have a healthy future. This paper examines the conceptual design of hybrid FC bus in London [1]. The research has been motivated by the need to solve urban transportation issues whilst minimizing initial cost and the recognition that hydrocarbon fuels are finite and increasingly expensive. The main requirements of the FC hybrid bus were established:

1. The FC hybrid power plant needed to fit on a standard type London bus without substantial changes to its dimensions, weight, seat count and daily performance.
2. The bus must be operable in London climes allowing for the range of ambient temperatures experienced over the annual cycle.
3. Sufficient power so existing performance, routes and stop times are not detrimentally compromised.
4. Auxiliary equipment to be considered such as hydraulics and pneumatics, as these are currently mechanically driven directly using the ICE.
5. FC specific power needs to be no less than 300 W/kg to achieve the standard of Fuel Cell performance and reliability as proposed by USABC [2], [3].
6. Refilling of H_2 fuel needs to be simple and quick and the safety requirements for H_2 must be observed.
7. Maintenance demand of a hybrid FC bus should not be arduous and certainly not excessively greater than ICE.

II. VEHICLE SELECTION

London has more than 7,000 buses and the vast majority are ICE powered emitting some 1.3 kT of CO_2 and other emissions across London on many different routes [1]. The route chosen for the FC hybrid bus study is London route 226 which uses the Alexander Dennis Enviro200 Dart bus that can carry 55 passengers as shown in Figure 1. Route 226 runs from Ealing Broadway Station to Golders Green Station, as Figure 2 shows, a distance of 15 km with 40-50 minute estimated running time. There are 26 stops more or less equally spaced. This route was selected as the ICE bus emits high level of emissions during acceleration due to the high number of stops, traffic lights and traffic density and the 45 minute running time allows for regular fuel recharging at the end of each leg. The Alexander Dennis Enviro200 Dart is used on this route and has the dimensions shown in Table 1 which is a very popular bus in London.

TABLE 1
ALEXANDER DENNIS ENVIRO200 DART BUS DIMENSIONS [1] [4]

Length	1025 cm
Width	244 cm
Wheelbase	510 cm
Weight	12,000 kg

Fig. 1 Alexander Dennis Enviro 200 Dart bus at route 226

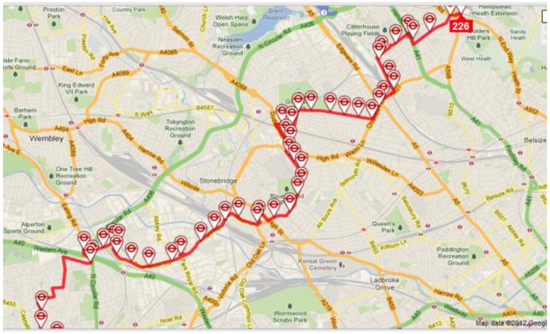

Fig. 2 London bus route 226 in Google map [1]

III. HYBRID SYSTEM DESIGN

Series hybrid propulsion is known to be a suitable solution for urban public transportation where frequent acceleration and de-acceleration events occur without sustained high speed operation. In a FC hybrid drive the key is to balance the power rating of the FC and the energy storage requirement which must be optimized considering technical and economic issues.

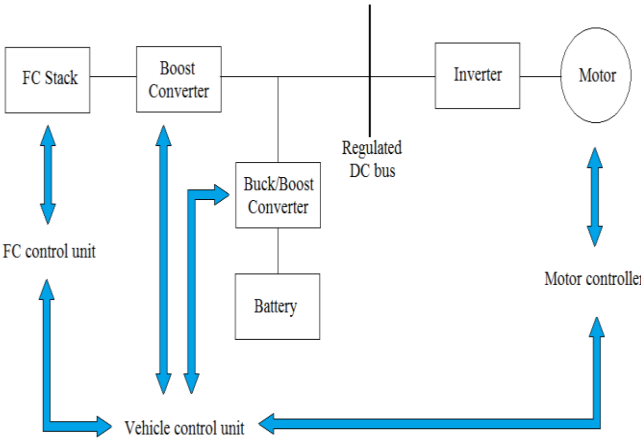

Fig. 3 Typical FC hybrid system with controllers [5]

Considering Figure 3, the FC stack reaction occurs through adding H_2 and O_2 from air to produce electrical power, waste water and waste heat. The output electrical power is used for propulsion and auxiliaries with any excess power being fed to the battery. The fuel cell waste heat can be used to heat the cabin space (in winter) or vented via a radiator. Waste water, the product of H_2 and O_2 reaction, is exhausted at around 80 °C as a mixed vapour and liquid. Hydrogen is more easily stored in bottles in compressed form at pressures of 200-300 bar. A clean compressed air source is necessary to avoid poisoning the fuel cell. The fuel cell acts as a constant on/off power generator operating at its efficient load point to minimize H_2 consumption whilst the battery acts as to supply or absorb energy or float. The battery depletes its energy to supplement fuel cell power when the bus accelerates, absorbs energy when the fuel cell's supply of electrical power is greater than demanded and also used to capture regenerative braking energy. When power demanded equals fuel cell supply of electrical power then the battery simply floats neither absorbing nor providing energy. A further refinement is that the battery can be recharged via a plug or inductive loop whenever the bus is idle for reasonable periods. The operation can be summarised as four modes shown in Figure 4. The electrical loads are the propulsion drive unit and the onboard auxiliaries. In ICE buses auxiliary loads such as hydraulics and pneumatics are mechanically driven off the engine whilst in a FC hybrid bus auxiliaries must be electrically driven.

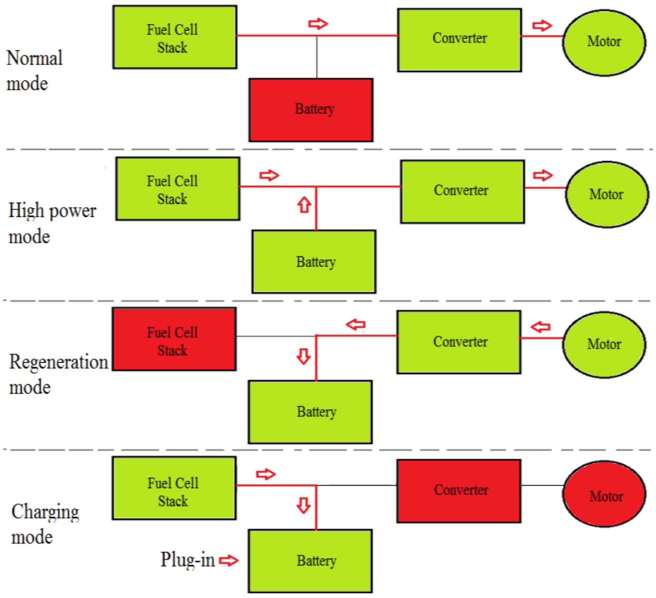

Fig. 4 FC hybrid bus operation modes

Power management and conditioning is essential to make the FC, battery, propulsion motor and auxiliaries work together to maximize efficiency and minimize emissions. Referring again to Figure 3, then the FC stack is connected to the DC link using a boost converter with a series connected diode arrangement to prevent reverse power flow. The battery is connected to the DC link using a bi-directional converter since the energy can both be taken from (discharge) and fed to the battery (charge) and also because the rate of charge and discharge needs to be controlled carefully to ensure battery lifetime is assured. Auxiliary loads requiring substantial power such as the hydraulic steering pump, air compressors for pneumatic braking and air conditioning are fed from the DC bus. Additionally a low voltage DC system is needed for lights, wipers etc. and is provided for using a DC/DC converter with stabilized 24 V DC output.

Table 2 summarises the major DC-DC converters that were considered. A conventional boost converter has been selected for use with the FC because it is cheap, easily to control and can boost the low voltage output from the FC. A full bridge buck/boost converter has been selected for the bidirectional converter [6]. The full bridge converter offers an efficient, inexpensive, stabilized low current and voltage ripple, ease of control.

TABLE 2
DC/DC CONVERTER TOPOLOGIES SUMMERY
[6] [7] [8]

Option	Advantages	Disadvantages
Boost converter	Simple Cheap	No electrical isolation
Full bridge converter	Electrical isolated Suitable for high power	
Half bridge converter	Electrical isolated Cheap	Low efficiency Hard to keep symmetrical
Voltage doubler	Electrical isolated Small transformer Low current ripple	Complicated control
Soft switching direct converter	Electrical isolated	Complex components
Fly-back converter	Electrical isolated Step up voltage	Low efficiency
Multi-device interleaved converter	High efficiency Reliable	Very complex circuit and control
Current fed converter	Electrical isolated	Extra cost by inductors

IV. VEHICLE SUBSYSTEM

These include the flow control subsystem, heat control subsystem, water management subsystem, and power management subsystem [8].

A. Flow Control Subsystem

The flow control subsystems include the control of H_2 and air. H_2 is supplied by high pressure cylinder. The bus will need 5-10 cylinders depending upon type (pressure) selected to ensure the bus has sufficient fuel energy to operate over the required distance. H_2 safety is a critical issue for the FC bus so the location of the H_2 bottles is an important consideration. To control the flow of H_2 a control system is required including a pressure relief valve, regulator, safety valve, pressure gauge, flow gauge, heat exchanger and leakage detector. In order for the FC to use O_2 from atmospheric air, a compressor and vaporiser is used to increase its pressure and humidity to improve the reaction speed of the FC [1], [8]. Controlling the H_2 and air flow rate prevents the FC generating excess power and at low loads the fuel cell is more efficient.

B. Heat Control Subsystem

Heat will be produced by the FC primarily because of its internal resistance characteristics so it must be cooled. The most appropriate way of cooling the FC is to dissipate heat through a water circulation system and radiator using cooling air. The cooling air may be fed to the inside the cabin or else dumped to atmosphere depending upon cabin temperature. Cabin recirculation of air is also possible in extreme cold conditions. It is important that the cooling system is arranged so that the temperature of the fuel cell remains more or less stable to minimize thermal cycling [8].

C. Water Control Subsystem

FC reaction will result in varying amount of exhaust waste water [9]. Brindhan carried out the research of water production from a PEMFC [10]. It is estimated that 9.4 litres of water will be produced for each hour of bus operation. Assuming the bus operates 8 hours per day then the bus will produce approximately 450 l water. A tank able to store up to 500 l water is needed if the water is to be stored else the alternative is to allow the water vapour to escape to atmosphere and cool the liquid water using an air heat exchanger before dipping onto the road.

D. Power Management Subsystem

The power management subsystem includes the management of power source and electrical system. Since the vehicle will have two power sources, FC and battery, the hybrid propulsion system needs to be optimized for operation efficiency. The energy flow and losses are shown in a Sankey diagram in Figure 5. The Sankey diagram indicates the approximate losses at each stage of the bus operation: Electrical power is produced by the PEMFC and heat loss occurs; the next stage includes losses of accessories and power conditioning which occur for example as conduction and switching losses in the converters; the battery will supply or absorb the electrical output from FC depending on the operation mode but there are converter losses; the power flows to the propulsion motor where it is converted from electrical to mechanical power. The final stage to the vehicle is traction power to the wheel with losses in the gearbox, bearings and tyres.

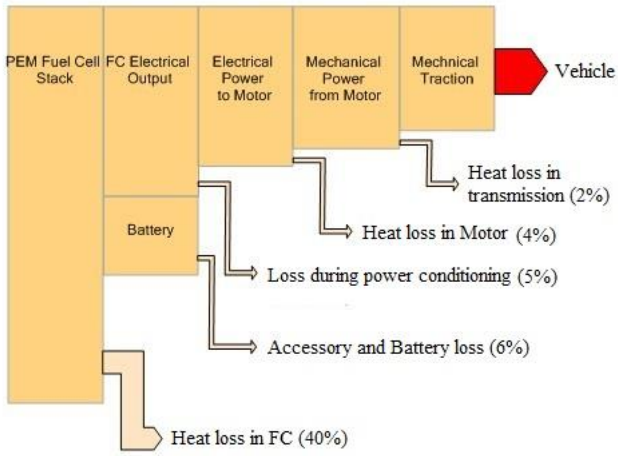

Fig. 5 Sankey diagram showing the energy flow of the FC hybrid bus

V. VEHICLE REENGINEERING

The FC hybrid drive bus is based upon the original ICE bus in the same way that diesel hybrid drive bus has emerged from the original ICE bus. The ICE along with mechanical driven auxiliaries were removed and replaced with FC, battery, controller and electrically driven auxiliaries. A 3D schematic of the FC hybrid bus layout is given in Figure 6 and details provided in Table 3.

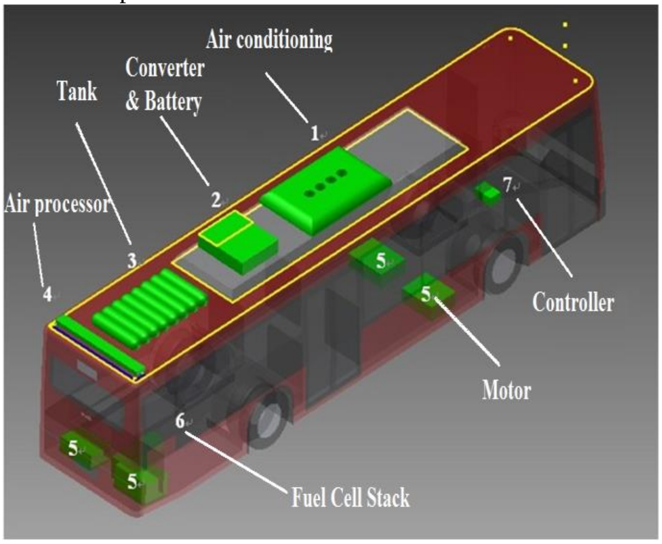

Fig. 6 3D schematic of FC propulsion bus [1]

Key aspects of the design are:

- 6x20 kW PEM FC stack are located in the lower part of the bus at its rear end with its cooling system with radiator mounted so an air cooling system is in proximity to the cabin.
- Six cylinders tanks, each at a pressure of 350 bar, are installed on the roof of the bus. The total capacity of H_2 is 20 kg giving a 102 miles range [1]. This means recharge is needed about every 10 route completions. H_2 cylinders are located externally at the trail of the bus for added safety, to minimize the impact of H_2 leaks and for ease of recharging.
- The power management control unit, including the motor controller and FC control unit, is located in the cabin space to allow ease of access.
- Four AC three phase induction machines with their gearboxes have been selected as the traction force for the bus wheels and are located near each wheel.
- The power conditioning units include DC/DC converter and DC/AC inverter. The 60 kWh Li-ion battery is located in proximity to the converters on the roof.
- The design of the auxiliaries include electrically driven air compressor unit, hydraulic system, air filtering and processing system for the FC and an air conditioning system.
- Air conditioning unit is used for air conditioning control inside the bus. During winter the FC stack excess heat may be used to assist air conditioning.

VI. VEHICLE PERFORMANCE

Table 3 outlines the key specifications of the FC bus. The operation performance and specification is based on the previous report.

TABLE 3
FUEL CELL BUS SPECIFICATION AND ESTIMATED PERFORMANCE [11] [12]

Fuel Cell	PEM
Fuel cell stack output	6 x 20 kW
Battery	60 kWh Li-ion
Peak torque	160 Nm
Absolute Top Speed	65 mph
Operation Temperature	-40°C to +125°C
Range	100 miles
Dimension (L*W*H)	1070*244*262 cm
Seats	29
Emission	H_2O (if not tanked)
Bus lifetime	15,000 hours
Hybrid type	Series, charge sustaining
Regenerative Barking	Yes
Fuel Capacity	20 kg H_2
Controller	EV control
Fuel economy	5.1 miles/kg H_2

VII. VEHICLE VIABILITY

The FC hybrid bus is designed to replace the ICE bus that commonly operates in London and also in other main cities around the world. The viability of a FC bus replacement needs to consider wider aspects than just financial although this is important for cost-benefit:

A. *Why FC hybrid propulsion*

The FC is advantageous because it offers superior efficiency, less vibration, zero harmful emissions, and flexible operation when working with an energy storage unit. A FC hybrid bus is cheaper than pure FC bus with the same power specification because the price of smaller fuel cells is generally less than large fuel cells. Hybrid propulsion gives benefits from operating the FC at constant power and allowing for regenerative braking. No major structural changes are needed when converting an ICE powered buses into FC hybrid powered bus. Comparing with ICE, less maintenance will be need to be carried out because there are less mechanical moving parts.

B. *Cost Estimation*

Considering initial costs, the FC cost has fallen 80% since the last ten years [13]. The Fuel Cell system is estimated to be £1.5k per kW for a FC system and £2.5k for the complete fuel cell power unit rated at 120kW [12]. In addition, to the fuel cell there are costs associated with H_2 storage, Li-ion battery, electric motor drive chain and the power management system. Further costs are associated with electrical drives for the auxiliaries and of course the integration of the system. The total cost is estimated as £190k therefore much higher than the standard diesel vehicle as £100k, however is 50% lower than a pure H_2 FC bus [14]. The breakdown of costs is shown in Table 4.

The running cost of the FC hybrid bus needs to consider the price of diesel and the price of H_2. These prices are £1.4 per litre of diesel and £8 per kg of H_2. This means the cost of operating the FC hybrid bus is £1.6/mile compared to the diesel bus at 40p/mile.

TABLE 4
FUEL CELL BUS COMPONENT COST ESTIMATION
[1] [15]

Component	Cost	For bus
Battery	£11k	£12k
Fuel Cell	£1500/kW	£1500 x 120 = £180000
Motor	£7.8/kW	£7.8 x 120 = £936
H_2	£8/kg	£8 x 20 = £240

C. Emission Calculation

Assuming an average bus in London operates 125 km per day. The emission can be calculated according to the emission coefficient for a ICE bus as Table 5 shows.

TABLE 5
EMISSION COEFFICIENT PER KM OPERATION
[1]

Emission	Coefficient (g/km)	Emission of 125 km operation
Carbon monoxide (CO)	0.7	87.5 g
Volatile organic compound (VOC)	0.2	25 g
Nitrogen oxide (NO_X)	1.8	225 g
Carbon dioxide (CO_2)	1475	184.4 kg
Particulates	2.7	337.5 g
Total Emission per bus daily		185.1 kg

Every ICE bus replaced by a FC will reduce harmful gas emission 185 kg each day within the city. It is recognized that the emissions associated with H_2 production must be accounted for however the more fuel cell bus replaces the ICE buses, the less emission will be produced within the city environment which benefits large number of people.

VIII. CONCLUSION

This project considered the conceptual design and operation of a FC hybrid bus. The FC bus has been designed having a series hybrid propulsion system with PEM FC and Li-ion Battery. This bus achieved the characteristics of zero emission, low noise, easily start-up and low vibration meaning it offers FC bus a potentially promising prospect for urban transportation. Enviro 200 bus has been one of the popular buses used in London and this ICE powered bus has been considered replacing the ICE with a FC hybrid power plant. The hybrid bus design topologies have been reviewed with different operation modes. The subsystems needed for the FC hybrid bus has been identified. The first cost of FC hybrid bus has been estimated to be £190k and operating cost is £1.6/mile. Route 226 is just an example of a route which will benefit from switching to FC hybrid bus and there are hundreds of buses routes in London so similar analysis can be applied. All in all the switching of the standard ICE powered buses and taxis to clean energy will be a promising move and is likely to be initiated by rising gasoline price and more restricting emissions limits.

Further work can be done to improve the performance of the FC bus. Light-weight material can be considered to solve the extra weight problem caused by the H_2 tank and motors. If the supporting facility can be optimized to achieve a faster refuelling, then the bus can optimise the number of H_2 cylinder and the size of battery to achieve a better power performance and further reduce the cost.

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