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EUROPEAN DEVELOPMENT OF A FUEL CELL POWERED SCOOTER

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Introduction

Today in Europe there are 23,000,000 two-wheeler vehicles on the road. Where the small 50 cc two-stroke engine vehicles are especially popular in the cities, there is a growing market for larger type scooters with typical urban use. It is expected that the market share for these types will eventually reach ca. 25 %. In addition to being very popular and convenient for city and urban use, scooters may constitute a future environmental and health problem, as presently seen in a number of Asian cities and urban area. Where more and more cars meet Euro III pollution limits, the majority of two-wheeler vehicles only meets the Euro II standard. A penetration with clean fuel cell driven vehicles of only 10 % in the 2006 market of larger type scooters would already mean a reduction per year of 880,000 kg CO; 192,000 kg hydrocarbons and 48,000 kg NOx. Including the huge market of 50 cc scooters could lead to reductions of 640,000 tons CO; 320,000 tons hydrocarbons and 8000 tons NOx in 20 years from 2006. However, weights and volumes of fuel-cell systems in the relevant power range have been long in contrast with what could be accommodated in the limited space available in a scooter. Exploratory work in the period 1998 to 2000 by ECN and Piaggio & C Spa has shown the feasibility of dedicated fuel cell plus supercapacitor power systems for large type scooters. It is expected that on the longer term, when miniaturization of the technology is fully developed, also the small 50 cc type scooters can benefit from this clean way of propulsion.

The FRESCO Project

In January 2002 the project "FRESCO", Fuel-Cell Reduced-Emission Scooter, partially funded by the European Commission through the 5th framework program, has been started. In this project a *prototype fuel cell driven scooter* will be developed, built and circuit-tested by the end of 2004. The European consortium carrying out this project consists of Piaggio & C Spa (Italy) responsible for the overall vehicles system, building and circuit testing, Selin Sistemi Spa (Italy) for developing the electric rotating machine and traction converter, ECN (The Netherlands) for the fuel-cell stack and supercapacitor module, and CEA (France) responsible for the development and fabrication of the high-pressure hydrogen storage tank. The scooter will be a modified, modern mass-production type, will have a maximum speed of 75 km/hrs, a range $\geq$ 100 km and further state-of-the-art characteristics. A *supercapacitor module* will support the fuel-cell stack to optimize system behavior and to facilitate for regenerative breaking. An *advanced system concept* is chosen, aiming at reduction of electronic hardware, simplicity in system control and high system stability.

System Concept and Modeling of System Component Ratings

Models of FCEV systems have been built in Matlab / Simulink. The basic model blocks for the system components are obtained from the QSS-Toolbox by the ETH Zürich and from NREL's ADVISOR. These blocks are customized to the actual needs and complemented with a control algorithm. The resulting tool is a quasi-static, back-wards-facing model. A quasi-static model assumes the system to be at equilibrium at each simulation time-step. This approach is chosen because this kind of simulations typically precedes the component development stage. Hence it is not always possible to obtain sufficient data to feed a dynamical model. The main goal of the simulations is to determine component power ratings of the FC stack, the EC module and the traction motor and converter, based on performance requirements resulting from the vehicle parameters and a drive-cycle. In addition, the model is used to estimate performance indicators like fuel consumption, carbon dioxide and other emissions. Here, the capacity of the hydrogen tank necessary for the desired vehicle-mission range is also determined.

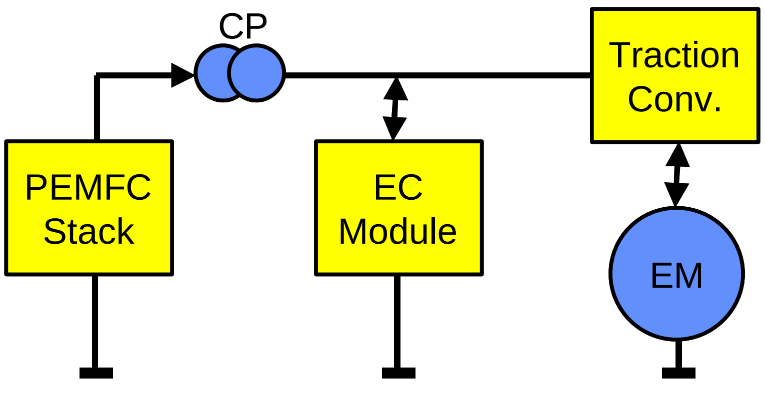

Figure 1. The system concept chosen allows a large voltage swing on the rail. The advantages are the avoidance of a DC/DC converter, simple system control and very good system stability.

The modeling has been carried out for various system concepts and using a drive-cycle obtained from Piaggio field data on the typical use of scooters. The system concept shown in *Figure 1* has been selected, because it allows for an optimum efficiency, mini-mum component requirements and hardware needs, and simple system control. Note that a large voltage swing on the rail is allowed, i.e. from the maximum EC voltage to half of that vol tage, and that regenerative breaking is incorporated. This concept avoids the use of a DC/DC converter between the rail and the EC module and is characterized by very good system stability.

Sizing and Accommodation of System Comp onents

Given the selected system concept and the power and energy ratings of the various system components, the geometrical size of the co mponents has to be estimated. This is done by using the specialized design tools for the FC stack, EC module, hydrogen tank, etc. Subsequently , at Piaggio a 3D-CAD approach is used to fit the components with their typical shapes and sizes in the frame of the scooter. Modifications in component designs or selections may be required for successful accommodation. This iterative process is often cal led the building of the "virtual veh icle". The final result for the FRESCO prototype scooters is shown in *Figure 2*, indicating the feasibility of the FC + EC system for this urban -use vehicle. In this particular case the use of an EC module based on availa ble technology has already significant weight and volume advantages over batteries. However, for commercial scooters further volume reduction of components, especially those directly under the driver seat, are favo rable.

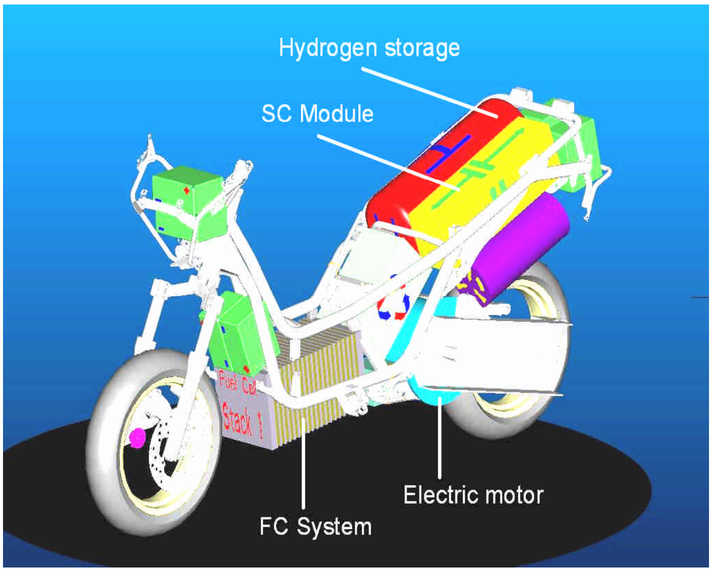

Figure 2. The virtual vehicle. Piaggi o's X9 frame with fuel cell stack plus supercapacitor module drive train. Hydrogen is the on-board fuel. The prototype system component sizes are estimated with model calculations.

Development of the PEM Fuel Cell Stack

The shape of the fuel cell stack has been adapted to the shape of the space available in the scooter. The stack therefore has a double trapezoidal base with maximum dimensions 420 x 280 x 205 mm, as shown schematically *Figure 3*. The left and right triangular portions of the cross-section are used for gas manifolding. A rectangular centre part remains, comprising the active cell area and an upper and lower part for the coolant manifolding. The resulting active area is about 280 cm^2.

The electrical requirements for the PEMFC stack resulting from the modeling described above, are a power of 7.7 kW and a minimal voltage of 51 V. The corresponding maximum current is 151 A, the current density 550 mA/cm^2. At this current a voltage per cell better than 600 mV can be expected at atmospheric conditions, when using Nafion 112 as membrane and 0.35 mg/cm^2 platinum loading on each side. Consequently, the required number of cells has to be 85. To accommodate this number of cells the thickness of each is only 4.25 mm; this includes graphite composite flow plates of about 2 mm in thickness.

The stack is operated at ambient pressure hydrogen as fuel. The hydrogen will be re-circulated yielding a relative humidity better than 70%. The incoming air is humidified through a membrane exchange humidifier with the wet exhaust gas. A dew point in the order of 55 ^{o}C can be achieved. The feed gases flow in semi co-flow configuration. For both special flow fields are realized, one at each side of a flow plate, in order to have a pressure drop that is low, but still sufficient to remove water droplets from the cell.

Figure 3. The special shape of the fuel cell stack allows for optimum use of the available space. The right-hand-side of the figure shows a single cell with its flow plates and end plates. The performance of the single cell was successfully verified; multi-cell tests are in progress.

Supercapacitor Development

Requirements for the EC module follow directly from the modeling calculations of the required power and energy and the allowable volume and weight in the virtual vehicle. It turns out that existing EC technologies are sufficient for the prototype vehicles, but have to low *energy density* for application in the final commercial scooter. In the same way, battery technologies suffer from to low power density. Also it turns out that for this particular case the improvement of energy density of supercapacitor technology is the strategy to be preferred over the one of power density increase of batteries.

Currently available EC technologies often have two high-surface-area carbon electrodes and thus rely on pure double-layer capacitance. The increase of energy content of supercapacitors is pursued by the use of so-called pseudo-capacitance. A well known material showing this property in KOH electrolyte is $Ni(OH)_2$. However, this electrode material has a number of disadvantages limiting the effect of this approach, i.e. a limited usable voltage window and a low and state-of-charge dependent electrical conductivity. In addition, as a nickel compound it has environmental and health drawbacks. At ECN a well-defined screening strategy has resulted in the identification of two new classes of materials with very promising properties for the application in supercapacitors. The classes have been named EMX and EMZ. The materials do not contain any precious elements and are therefore low cost. Some of the relevant properties of EMX-1 are shown in *Table 1* in comparison with known electrode materials. Using a simple geometrical model for the EMX-1 / KOH / AC technology, the attainable energy for cells and modules has been estimated. Energy densities ≥ 15 Wh/kg may be obtained, where presently available technologies are limited to ca. 5 Wh/kg. For the particular case of the FRESCO scooter, the application of the EMX material would ideally result in a reduction of mass by a factor of two, and a reduction of volume by a factor of three. Present research concentrates on the optimization of material composition and microstructure, and on fabrication technology for EMX electrodes. The development of a prototype supercapacitor module based on EMX material is part of a project that runs in parallel to the FRESCO project. First prototypes are made in co-operation with CORUS Technology BV (The Netherlands) and with ELIT Co (Russia).

Table 1. Comparison of the main properties of supercapacitor electrode materials.

	AC	RuO_x	NiOOH	EMX-1
Sp. Area (m^2/g)	1500	120	120	≤ 50
Capacity (mAh/g)	14	98	90	≤ 170
Conduct. (S/cm)	< 1	~300	< 10	5000
Price (Euro/kg)	2.0	3000	> 6.0	< 20

Other System Components

The fuel cell stack and the electrochemical capacitor module together with a so-called current pump to match their electrical characteristics form the *electrochemical engine*. The electrochemical engine is capable of autonomously reacting to power requests (within its maximum rating) if provided sufficiently with hydrogen and air. Hydrogen is stored in high-pressure tanks made of composite material. The electric rotating machine is of the AC synchronous type with permanent magnet and is connected to the rail through a bi-directional traction converter, allowing for regenerative breaking. The converter includes a voltage step-up function; the higher voltage facilitates compactness of the rotating machine. Another crucial part of the system is the cooling circuit, dealing with the cooling demands of the fuel cell stack and of various electronic components like the current pump and the traction converter.

Figure 4. Piaggio's X9 has been selected as the scooter to be equiped with an electrochemical engine. The present commercial product has a 4-stroke internal combustion engine.

Acknowledgements

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