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Energy Design of a Fuel Cell Supply System for Electric Bicycle

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Abstract

The paper is concerned with the energy design of a fuel cell supply system for electric bicycle. A suitable architecture for the supply system is at first arranged. Besides the fuel cell, it includes an hydrogen tank and a supercapacitor bank directly connected to the dc link of the propulsion system. After selecting the fuel cell and illustrating its operation, the hydrogen tank and the supercapacitor bank are designed, respectively to meet the specifications for the range (100 km) of the bicycle and for the regulation of the dc link voltage. Then, the fuel cell supply system is set up, fitted up in a bicycle and tested. The test results corroborate the design procedure.

Keywords: Bicycle, Fuel cell, Power management.

1 Introduction

Electrically power assisted bicycles, shortly electric bicycles, are viable vehicles of personal travel for neighboring distances. Compared to human-powered bicycles, they give an average cyclist the chance of increasing the travel speed and range; compared to fuel-propelled vehicles, they abate pollution and traffic congestion in the towns; furthermore, they have the merits of not requiring any administrative fulfillment like registration, licensing and insurance [1].

According to the European Directive [2], an electric bicycle is a two-wheel vehicle “with an auxiliary electric motor having a maximum continuous rated power of 250W, the output of which is progressively reduced and finally cut off as the vehicle reaches a speed of 25km/h, or sooner, if the cyclist stops pedaling”.

Nowadays, the electric bicycles are powered by batteries that make the travel range limited and the recharge outage long. A solution of the mentioned problems is to power the electric bicycles with fuel cells (FCs) [3]; this solution is about to become practical due to the fall of the costs and the improvement in the energy performance of the FCs and the hydrogen storage devices.

In this paper, a FC supply system for electric bicycle is designed and set up. Besides the FC, the supply system includes an hydrogen tank, a dc-dc converter interposed between the FC and the dc link of the propulsion system and a supercapacitor bank directly connected to the dc link. The FC supply system has been fitted up in a commercial electric bicycle in place of the battery.

The paper is organized as follows. Section 2 presents the electric bicycle utilized as a case study and the architecture of the arranged FC supply system. Section 3 deals with the selection of the fuel cell and its operation. Section 4 determines the energy consumed to cover a typical urban cycle and designs the hydrogen tank. Section 5 outlines the dc-dc converter and its control. Section 6 designs the supercapacitor bank. Section 7 describes the set up of the FC supply system and gives the results of some tests on the FC-powered bicycle. Section 8 concludes the paper.

2 FC supply system

2.1 Electric bicycle

The electric bicycle of the case study is a top-level product of an Italian company [4]. Its propulsion system can be divided into two subsystems connected through a dc link, namely the supply system and the traction system, as shown in Fig.1. The supply system consists of a 24V, 8A·h NiMH battery whilst the traction system is made up of a brushless dc drive with gear motor. The drive utilizes a voltage-controlled inverter and does not recover the energy during braking. The motor is incorporated in the hub of the rear wheel and is coupled to it by means of a planetary gear.

The rated values of voltage, power, and efficiency for the electric drive are 24V, 250W, and 0.7 whilst its maximum supply current is 15A. The mass of the electric bicycle is 24kg and its range is 25km at the nominal speed of 23km/h. The electric drive is activated by pedaling and draws the maximum current up to bring the bicycle at the nominal speed.

2.2 FC supply system architecture

The FC supply system is intended to replace the battery of the electric bicycle, by generating exactly the same voltage and current required by the traction drive. The design specifications for the FC supply system are the range of the FC-powered bicycle (100km) and the regulation of the dc link voltage (less than 5% of the dc value).

The architecture of the FC supply system is delineated in Fig.2. The hydrogen tank together with the FC delivers the electric energy. The dc-dc converter boosts the FC voltage and regulates the dc link voltage at 24V. The supercapacitor bank assists the regulation, especially under power transients. The FSS electronic control unit (FSS-ECU) commands the dc-dc converter and manages the operation of the FC supply system.

3 FC

FCs convert chemical energy into electric energy via an electrochemical reaction. A FC with the proton exchange membrane (PEM) technology is the natural candidate for vehicular applications since it has low operating temperatures (about 70°C), good power densities (about 0.7kW/l), quick standing start (around 30s), fast transient response (around 1.5s), and potential of low costs for high-volume manufacture [5]. Consequently, a PEM FC

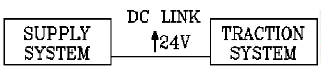

Figure 1: Propulsion system

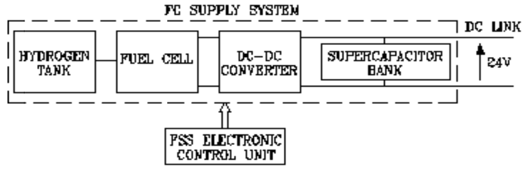

Figure 2: Architecture of the FC supply system

has been chosen for powering the bicycle. The reactants of the FC are hydrogen and oxygen and the outcomes are, besides electric energy, heat and water. With an envisaged efficiency of 0.65 for the whole electromechanical conversion down the FC stack (dc-dc converter plus traction drive), the power requirement for the FC is 385W.

Running through the shortlist of the supplying firm [6], a FC with rated power of 250W and maximum power of 363W has been selected. It comes with an assembly set composed of a FC stack, two blowers: the reaction and cooling blowers, two valves: the input and purge valves, and a FC electronic control unit (FC-ECU).

The FC stack contains 22 in-series cells. The reaction blower pushes the air with the oxygen on one side of the FC stack at a pressure of about 1.5 bar. The input valve enables the hydrogen to flow toward the other side of the FC stack at a pressure of 1.5 bar, fixed by a regulator placed in between the valve and the hydrogen tank. Normally, the FC stack operates in the dead-end mode, i.e. all the entered hydrogen takes part in the reaction and there is no exhaust. The purge valve copes with a non-perfect reaction; its opening allows the resident hydrogen to go out so as the fresh hydrogen entering into the FC stack cleans the surface of the membrane and lowers its humidity. The FC-ECU continuously monitors voltage, current, and temperature of the FC stack and activates the reaction blower and the input and purge valves for the FC stack to operate in nominal conditions of hydrogen and air pressure, and of humidity; when necessary, it also activates the cooling blower to keep the FC stack temperature within the operating limits. A picture of the FC assembly set is shown Fig.3.

The voltage of the FC stack is highly dependent on the current and becomes less than an half passing from no load to full load, as pointed out by the single cell voltage-current characteristic of Fig.4. In nominal conditions, the power delivered by each cell is 11.3W and the related values of voltage and current are 0.67V and 17A. Correspondingly, the voltage of the FC stack is 15V and the power is 255W. Other data of interests of the FC stack are the current at 13V (24A) and the rise time of the

Figure 3: FC assembly set

current in response to a step request from 0 to 24A (1.5s).

When the temperature of the FC stack is lower than the nominal one (e.g. at the start) or the hydration level of the membrane is not right, the voltage-current characteristic of the cell shifts down and, hence, the FC stack voltage diminishes for a given current. The FC-ECU interprets a voltage less than 13V as a malfunctioning of the FC assembly set and automatically disconnects the FC stack from the external load to prevent the damage of the membrane. This also occurs when the voltage of the FC stack goes below 13V because of an overload, which means that the maximum current generated by the FC stack is 24A.

The best performance of a PEM cell is obtained when the membrane has a specific level of hydration: a lower hydration increases the membrane resistance and leads to a progressive deterioration of the cell; an higher hydration prevents hydrogen and oxygen from reaching the catalyst and reduces the reaction rate. At the cathode of a PEM cell, water is produced when the protons crossing the membrane react with the electrons coming from the external circuit and the oxygen. If the current absorbed by the load is too low or the cell temperature is too high, the produced water could be not enough to properly hydrate the membrane or could evaporate too quickly. On the contrary, if the cell temperature is too low or the current is too high, the produced water could stagnate in the cells causing the flooding of the membrane.

In order to guarantee the right hydration of the membrane, the standard FC assembly sets are equipped with humidifiers that adjust the humidity of the reactants. To comply with the needs of size, weight and complexity aboard the vehicles, the selected FC assembly set does not use any humidifier neither in the hydrogen nor in the air supply, and achieves the right hydration by exploiting the water produced by the reaction inside the FC stack itself. To this end a model of the FC stack is implemented in the FC-ECU and the hydration level of the membrane is estimated from the monitored current, voltage, and temperature of the FC stack. When the estimated hydration goes down the right value, the FC-ECU short-circuits the internal terminals of the FC stack and the cells are crossed by a current of tens of amps that is instrumental in producing the needed water. The short circuit lasts for a maximum time of 50ms and repeats with a minimum period of 20s; during the short circuit, the internal terminals of the FC stack are disconnected from the external ones so that, from the point of view of the load, the FC stack behaves as an open circuit with an interrupt in the power delivery. In case that the estimated hydration level of the membrane is too high, the purge valve is opened. When this is done, the opening time is 0.5s and occurs with a delay of 10s after the short circuit.

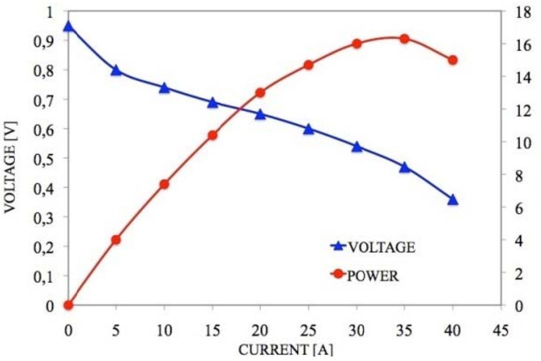

Figure 4: Single PEM cell electric characteristics

4 Hydrogen storage design

4.1. Energy consumption

The range of 100km for the FC-powered bicycle refers to a mission that is a repetition of the typical urban cycle of Fig.5. The cycle has a speed profile that can be experienced along urban outskirts. It is constituted by three stretches: an acceleration stretch with a peak power demand less than the one at disposal (time length of 40s, distance of 200m), a

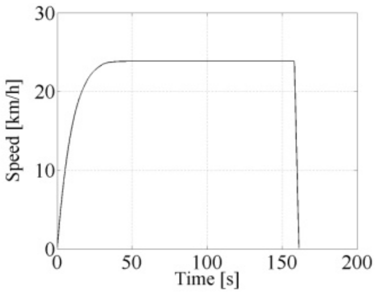

Figure 5: Cycle speed profile

constant-speed stretch travelled at the nominal speed (time length of 118s, distance of 790m) and a deceleration stretch (time length of 4s, distance of 10m).
To design the hydrogen storage, the energy consumption to cover the cycle is at first calculated. The calculation proceeds in two steps: a) formulation of the resistance forces, and b) calculation of the energy consumption by time integrating the instantaneous power demand along the first two stretches since the deceleration stretch is obtained by mechanical braking. The calculation is carried out by assuming smooth road and no wind.
For a ground speed v_{gr} and an acceleration a, the instantaneous power demand is

$$P = v_{gr}\left(F_d + F_{roll} + F_{add} + a m_{gen}\right) \quad (1)$$

where F_d is the air drag force, F_{roll} is the rolling resistance force, F_{add} is the additional friction force, and m_{gen} is the generalized mass of the vehicle, comprehensive of the masses of the bicycle and the cyclist, and of the inertial effects of the wheels. The air drag force is expressed as

$$F_d = \frac{1}{2} C_d \rho_{air} A_f v_{gr}^2 \quad (2)$$

where C_d and A_f are the drag coefficient and the frontal area of the electric bicycle and the cyclist, and ρ_{air} is the air density. The rolling resistance force is expressed as

$$F_{roll} = gm\left[0.005 + \frac{1}{14.5p}\left(0.15 + 1.74\left(\frac{v_{gr}}{100}\right)^2\right)\right] \quad (3)$$

where g is the gravitational acceleration, m is the total mass of the electric bicycle and the cyclist, and p is the tire pressure. All the quantities in (3) are in SI units, apart from the tire pressure that is in bar. The coefficients in (3) depend on the tires and road characteristics and are taken from [7]. It is worth to note that F_{roll} decreases by rising the tire pressure

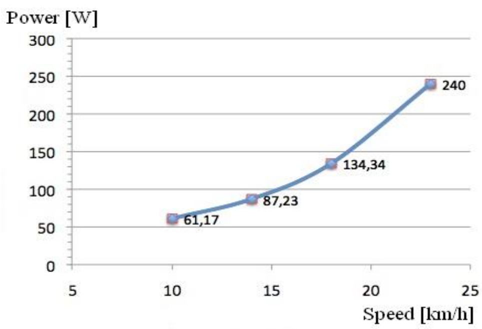

Figure 6: Measured electric power-speed relation

and varies with the square of the speed, like the air drag force. The additional friction force is due to bearing losses and is supposed to be constant and equal to 1N.
Eq. (1) has been verified by riding the electric bicycle at different speeds on an asphalt road with no wind. The measurements of the electric power delivered by the battery as a function of the speed are reported in Fig.6 and substantiate the equations (1)÷(3), if only the proper values are assigned to the involved quantities and to the traction drive efficiency.
With a cyclist of 80kg and a mass of the FC-powered bicycle approximately equal to the battery-powered bicycle, the mechanical energy necessary developed to cover the cycle of Fig.5 is calculated in 6.61W·h. Being the distance travelled at the end of the cycle equal to 1000m, the requirement for the mechanical energy to get a range of 100km is 100 times that of a single cycle, i.e. 661W·h. With an efficiency of 0.65, the electric energy delivered by the FC stack must be of 1017W·h.

4.2 Hydrogen storage

In nominal conditions the net efficiency of the FC stack, i.e. the efficiency after the energy drawn by the FC assembly set, is 43%. Then, the hydrogen tank must store 2.36kW·h of energy in chemical form to obtain the required electric energy. Since the lower heating value of the hydrogen is 2.78kW·h/Nm^3, the hydrogen to be stored must have a volume of 0.85Nm^3; it corresponds to a mass of 75g, being the hydrogen density of 89g/Nm^3. This means that the calculated hydrogen consumption in grams is 0.75 per km.
Hydrogen can be stored either in liquid form in refrigerated vessels, or in gas form in high-pressure bottles, or bonded with metals or metal alloys in low-pressure canisters. The last technology has been preferred [8] because it does not require a bulky cryogenic plant and does not pose the safety provisions necessary to handle high-pressure tanks; moreover, compared to the hydrogen storage in gas form, it behaves much higher energy density that, by definition, is the quantity of energy stored per unit volume of the device.
A metal hydride canister with a capacity of 0.750Nm^3 has been acquired [9]. It has the cylinder shape of Fig.7, with an overall length of 47cm, a diameter of 63mm, and a mass of 5.3kg. The charging pressure is 15 bar whilst the discharge pressure varies from 12 to 2 bar. The canister can work at room temperature, but better performance in terms of energy density, and adsorption and desorption rates are obtained if it is cooled during

Figure 7: Metal hydride canister

the charge and heated during the discharge.

5 Dc-dc converter

The voltage of the FC stack is less than the value due for the dc link and changes widely with the current. The dc-dc converter in cascade to the FC stack plays the twofold task of boosting the FC stack voltage and regulating the dc link voltage at 24V.
The scheme of principle of the dc-dc converter is shown in Fig.8. It has been designed by reckoning with the specification on the dc link voltage regulation and the following features of the FC stack: a) it is unable to absorb current, and b) an excessive current ripple impairs its lifetime. In accordance to point a), an unidirectional scheme has been implemented for the dc-dc converter, with the Schottky diode D and the Mosfet transistor T switching at 20kHz; the diode D_F is used to give a freewheeling path to the current of the inductance L under the FC stack power interrupt. In accordance to point b), the dc-dc converter is operated in continuous mode and the current ripple is set at a value less than 5% of the maximum FC stack current. From the data above, the inductance has been designed. The capacitance C smoothes the pulsating current at the output of the dc-dc converter; it is realized with a supercapacitor bank [11] and is designed in the next Section to meet the specification on the dc link voltage regulation under power transients since this condition is more stringent than the current smoothing action.
The supercapacitors are able to sustain only low voltages, usually less than 3V, and therefore are connected in series to form a module with a workable voltage. Moreover, they have an equivalent series resistance (ESR) that is roughly inversely proportional to the capacitance.
The control of the dc-dc converter as well as the management of the operation of the FC supply system is implemented in the FSS-ECU. The control is formed by an outer voltage loop closed around the dc link and an inner current loop closed around the FC stack current. The latter loop helps meeting limit and dynamics requirements for the FC stack current. The design of the control of the dc-dc converter and of the management of the operation of the FC supply system can be found in [10].

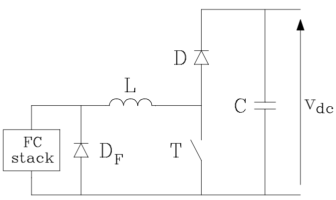

Figure 8: Dc-dc converter

6 Supercapacitor bank design

The supercapacitor bank partially feds the traction drive under a sudden power request because of the finite rise time of the FC stack current and fully feeds the traction drive during the FC stack power interrupt. A sudden power request occurs, for instance, at the standing start of the electric bicycle or when the road begins to go up. The maximum current I_M that here the traction drive can draw from the dc link is limited by the maximum current generated by the FC stack. By neglecting the losses, the balance of the input-to-output power for the dc-dc converter yields a value of 13A for I_M.
Two phenomena must be taken into account to meet the specification on the dc link voltage regulation: the voltage decrease across the capacitance because of its discharge and the voltage drop across the ESR.
Let us consider at first a sudden power request. In the worst case, the dc link must deliver a current that steeply increases from 0 to I_M. During the rise time of the FC stack current, the supercapacitor bank supplies the traction drive with a current that is the complement to I_M of the FC stack current referred to the dc-dc converter output. For a linear increase of this current, the discharge of the supercapacitor bank C is

$$Q_r = \frac{1}{2} I_M t_r \tag{4}$$

and the voltage decrease is

$$\Delta v_{dc} = \frac{Q_r}{C} \tag{5}$$

By (4) and (5), the discharge phenomenon imposes a value of C greater than 8.2F. Instead, the voltage drop across the ESR is

$$\Delta v_{dc} = ESR \cdot I_M \quad (6)$$

By (6), the voltage drop phenomenon imposes a value of ESR less than 92mΩ.

The catalog of a supercapacitor manufacturer has been consulted to find out the proper component [12]. Two equal supercapacitor modules have been selected, each of them with a capacitance of 58F, a maximum voltage of 15V and an ESR of 19mΩ, and have been connected in series to sustain the dc link voltage. Then, the dc link sees a capacitance of 29F and an ESR of 38mΩ. Note that the resultant capacitance is somewhat greater than the value calculated by (5), thus facilitating the regulation task.

The behavior of the dc link voltage following a sudden power request has been analyzed by simulation. The dc link has been steeply loaded from 0 to 10A at t=0.5 s and the voltages across the dc link and the capacitance have been traced in Fig.9 with the continuous and dashed lines, respectively. The traces show that at t=0.5 s there is a jump down of the dc link voltage due to the drop across the ESR. After that, the dc link voltage is the sum of two terms: the voltage drop across the ESR that linearly decreases in the same way as the capacitance current, and the voltage across the capacitance that also decreases but in the quadratic way due to the capacitance discharge. At about t=1.2 s the FC stack generates a current greater than the one drawn by the load and the capacitance begins to be recharged. As a result of Fig.9, the regulation of the dc link voltage is well within the specification.

The behavior of the dc link voltage following the FC stack power interrupt is still given, with good approximation, by the trace of Fig.9 going from 0.5s to 0.52s since there the contribution of the FC stack current is negligible.

The supercapacitor modules are equipped with an active circuitry that maintains an even distribution of the voltages across the single supercapacitors to prevent any dangerous overcharging of them. The current supplying the circuitry is drawn by the supercapacitors and, therefore, their voltage appreciably decreases along the time if their charge is not replaced.

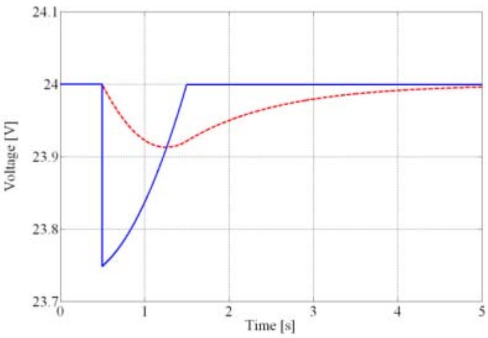

Figure 9: Dc link and capacitance voltages

7 Set-up and tests

At first, the FC supply system has been set up on the workbench and tested to verify its performance in terms of regulation of the dc link voltage and control of the FC stack current. Fig.10 reports these two quantities measured in response to a step current of 7A drawn from the dc link. The traces show that the dc link voltage is well regulated and that the FC stack current rises in the established time.

Afterwards, the FC supply system has been fitted up in the bicycle. A picture of the FC-powered bicycle is shown in Fig. 11. The hydrogen canister has been mounted over the top tube whilst the FC assembly set, the dc-dc converter and the FSS-ECU have been packed on the rear carrier. Outdoors tests have been carried out to measure the consumption of hydrogen and to verify the range of the bicycle. The results of three tests are given in Tab.1. Column D reports the travelled distance, column C the hydrogen consumption measured in grams using a precision balance, column C/D the hydrogen consumption in grams per km, and column R the range of the bicycle for a canister of 0.85Nm^3. In the last row of the table, columns D and C give the total distance covered and the total hydrogen consumed during the three tests. From them, average values are obtained for C/D and R. The results corroborate the design procedure. Indeed, the predicted hydrogen consumption is in good agreement with the prediction and the range of the FC-powered bicycle fulfills the specification.

Table 1: Measured data

	D [km]	C [g]	C/D [g/km]	R [km]
Test 1	2.3	1.85	0.8	94
Test 2	2.5	1.75	0.7	107
Test 3	3.4	2.40	0.7	107
Total	*8.2*	*6.00*	*0.73*	*103*

8 Conclusions

The paper has presented the design of a FC supply system for an electric bicycle. A particular attention has been paid to the design of the energy storage devices, such as the metal hydride canister and the supercapacitor bank, to meet the specifications for the range of the FC-powered bicycle and for the regulation of the dc link voltage of the propulsion

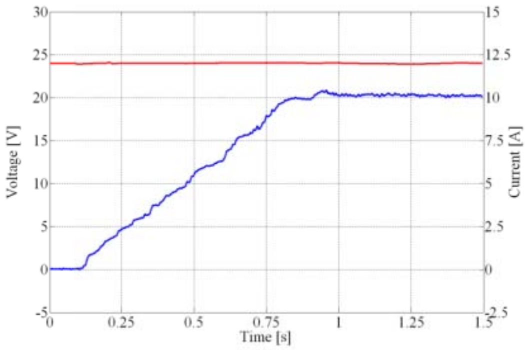

Figure 10: FC stack current and dc link voltage

system. Tests carried out on the FC supply system both at the workbench and after its fitting up in the bicycle have corroborated the design procedure.

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Fig. 11: FC-powered bicycle

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