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ENEA Hybrid Drive Train Testing Facility: a versatile instrument for HIL (hardware-in-the-loop) assisted design

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Abstract

Among the research and development subjects of ENEA (Italian National Agency for New Technology, Energy and Environment) an important theme is the study of innovative vehicles with high energy efficiency and low emissions. ENEA has set up an infrastructure in order to execute research and development activity for hybrid and electrical vehicles. The testing station offers a network of facilities covering almost all testing needs for single component, subsystems and complete vehicles.

The paper deals with features and working methods throughout the testing campaign of a FC emulator to characterize fuel-cell propelled drive trains. After a general discussion about the concept of Hybridisation Degree, the study focuses on the theme of optimal sizing for primary energy converter (fuel cell generator system) and electric energy storage (battery), according to the vehicle mission requirements. The experience demonstrates that HIL (hardware-in-the-loop) testing is a powerful instrument to overcome problems posed by behaviour of components like batteries and cost and complexity of others like fuel cells.

Keywords: Hybridisation degree, FC emulator, drive train testing, power fluxes analysis, hardware-in-the-loop

1 Introduction

To fully achieve the potential energy savings of a fuel cell vehicle (FCV) it is mandatory:

• to ensure the operation of the FC system at the maximum efficiency over the entire range of driving conditions encountered,

• and recover the braking energy, that in urban uses may be very relevant.

As a matter of fact, roller bench tests performed at Argonne National Laboratory (ANL) on Toyota Prius and Honda Insight [1], gave a fuel consumption reduction associated with the braking energy recovery ranging from a minimum of 3.5% (highway duty cycle) to a maximum of about 20% on urban duty cycles such as the Japanese J10-15 and the urban American cycles (LA4 and NYCC).

Both key targets can be obviously reached by a hybridisation approach for FCV, adding to the main energy source, the fuel cell system, an electric energy storage system [2].

A number of questions arises: what is the optimal sizing for both energy sources ? What are the main issues that influence energy consumption ? May testing help us ? What kind of testing ? and which experimental equipment ?

This paper intends to offer a contribute to answer these questions.

2 The vehicle mission and the hybridisation degree

A correctly designed storage system should contemporarily meet two requirements: i) the maximum power output necessary to compensate the difference between the generator power and the maximum power required by the vehicle (forecasted maximum power) and ii) the energy content sufficient to avoid the complete discharge during any power demand period (required storage energy).
The value of these two design parameters depends on two main factors: the design driving cycle and the hybrid system configuration, that are both expression of the vehicle's mission.
In series HEVs the system configuration can be represented by an index called "Hybridisation rate" or "Hybridisation degree" that is expressed by the ratio between the installed power source (generator) and the power required for traction:

HD (Hybridisation degree) = Pgen/Ptract.(1)

This concept was proposed first time by OAAT's in the "Vehicle High-Power Energy Storage Program"[3], and allows to state specific objectives for energy storage requirements that differ for different types of hybrid electric vehicles, Fig.1 at the end, among which FCHEVs (Fuel Cell Hybrid electric vehicles) are a particular case.

2.1 Optimal Hybridisation Degree

For a urban bus missions are predictable and the average power can be easily estimated. Therefore, a preliminary hybridisation degree can be calculated by the following formula

HD = Paverage / Pmax (2)

Moreover, the average power required is always a fraction of the maximum power required by the traction motor. Thus, if the power required by the motor is shared between two devices an economic benefit from cost reduction exists as storage devices heavier but cheaper than fuel cells are made. As a matter of the fact, storage devices having specific power equal to or higher than power generators are available at a lower cost than FC. In this way, the power system cost as well as the management cost is greatly reduced when compared with a full-power system since braking energy recovery can also be performed.

On the contrary, unpredictable mixed urban and extra urban cycles make very difficult to define a general optimal hybridisation degree for cars, and the hybridisation degree is generally higher than for busses (up to 100%), to be sure that the available continuative power will be enough in case of need.
As a result of the high power primary energy source, vehicles with high hybridisation rate mainly uses the storage unit for braking energy recovery and management of acceleration quick transients.
The availability of a high power generation makes it possible (in most cases) to continuously balance generator power and load even if transients are slow and controlled. As a consequence, the power flows in the vehicle can be managed with the generator always on (defined as "load following" mode, opposite to thermostatic or ON/OFF operation) and a duty-cycle close to 100%. The load-following mode shows a positive effect especially in vehicles powered by a fuel cell, whose performance curve is latter than ICE.
This approach does not give any plant cost reduction - except for the opportunity of managing the cell more smoothly, while designing a simpler generation system would translate into savings in management costs.
This lead to a more general question: is there an optimal value of the hybridisation degree from the point of view of fuel economy that would also allow weight and cost reduction of fuel cells? And, more and more important, is it possible to design such a hybrid power generation system by using only computer simulation?
The answer to the first question if yes (for extended bibliography, see [2][4]), on condition that the mission is well defined, that's not the case of a general purpose vehicle.
On the contrary, a perfect case from this point of view is a commuter train, whose mission is well scheduled (there is a timetable, there are not traffic jam and so on). The results obtained by Alstom [5] and NREL (National Renewable Energy Laboratories) for such a convoy, using as a simulation tool Advisor, are summarized in the table below.

Table1: Optimal sub-system power level sizing

	Empirical Value (kW)	Optimized value (kW)
FC maximum power	400	544
Electric storage maximum power	580	760
Energy consumption	100	79

The result is apparent: using such tools gave up to 21% of energy saving vs,. empirical sizing and tuning. But, and this is the real question, how much reliable is such result?
The answer requires a more deepened investigation, and, generally speaking, we cannot be sure about this way to dimension the system, because the powertrain of a HEV is a complex non linear system, mainly because the presence of the electric energy storage, that is very difficult to simulate. Batteries energetic efficiency, e.g., is still debated in the scientific community, especially with respect to the knowledge of the efficiency in real operating conditions of a running vehicle [6]. This variable in fact is tied to the cinematic cycle in which the vehicle is employed, to the modalities of recharge, to the temperature, to the aging, etc.
Only experimental tests are reliable in this case, and it is important to support the design phase with appropriate battery (or power train) testing, Fig.2.

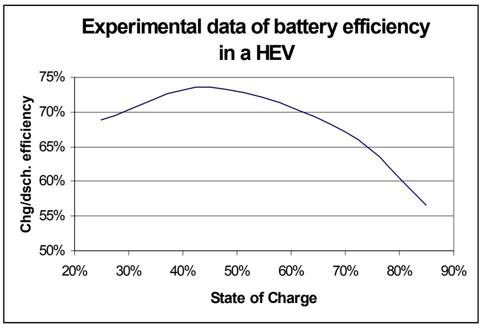

Fig.2, Battery Efficiency in "real world " use [7]

Therefore, the availability of a test bench capable of performing real time and HIL simulations, where devices like batteries are not simulated but really operating, is of outmost importance to ensure fast and reliable powertrain design.
To give a real example of such a test bench, the Tsinghua University test bench is shown, Fig.3 at the end of the paper. It has been set up to simulate a fuel cell powered hybrid vehicle in the framework of the national project 863 for a fuel cell city bus [8].
A similar test bench, a Drivetrain Test Facility, was designed in ENEA (the Italian National Agency for New Technologies, Energy and the Environment) and realized by ASSING, its features are described in the following section.
An example of its use, in the framework of a research project carried by CRF (Fiat Research Center) and ENEA is given in the last part of the paper.

3 The ENEA Casaccia facility

Among the research and development subjects of ENEA an important theme is the study of innovative vehicles with high energy efficiency and low emissions. Testing and evaluation activities play a strong role in this program, through components and subsystems characterization in a Drivetrain Test Facility, while complete vehicles are tested on a Roller Bench.
The Drivetrain Test Facility comprises a test bed for complete drivetrains of electric and hybrid vehicles powered by batteries and fuel cell.
Series Hybrid Vehicles are equipped with an electric driving motor, an electric storage capacity and an energy generation system, like a combustion engine coupled with a generator or a fuel cell. Each of these is a subsystem of the driving systems and the facility is equipped with testing sections for each subsystem. The different sections have been integrated and are centrally managed, therefore they able to operate together or alone, in the event of partial test. Apart from control and data acquisition room, we can identify three section:
• Power generation
• Energy storage and management
• Driving motors

3.1 Power generation system test bench

The power generation system testing facility, Fig.4, allows operation of motor generators and turbo generators up to 40 kVA and fuel cell up to 25 kW. It has been equipped with :
• liquid and gaseous fuel supply, including hydrogen
• electric power take-off
• data logging systems
• safety and fire prevention systems

Fig.4, Elliott TG 45 on testing

3.2 Energy storage test bench

The testing facility, Fig.5, is equipped with AC/DC bidirectional converter able both to charge the batteries and to discharge them to prefixed DOD conditions, so enabling them to supply electric motors, simulating every real operating conditions.
The equipment is able to supply power to the motors, when they are not being powered directly by batteries, to simulate a motorgenerator or a fuel cell system,

Fig.5, battery cycler and climatic chamber

Operational limits are 60 V (minimum voltage) up to 360 V, and 100 kW as maximum power. For thermal conditioning of storage system there is a thermal chamber also.

3.3 Motors & engines test benches

The testing facility allows experiments on : • internal combustion engines for conventional and parallel hybrid vehicles, with liquid or gaseous fluid supply, operating alone or together with electric motors on the driving shaft • electric AC and DC motors, with their supply systems It has been equipped with a 100 kW (150 kW maximum) test bench of the type “reversible electric machine operating on 4 quadrants, Fig.6, and two 30 kW (50 kW maximum) test bench of the same type, Fig.7. Each test bench, RIGAL model, is equipped with the DYNAS software, designed and developed by ASSING S.p.A., a leading Italian company that provides “turnkey” solutions, plants and automatic control systems for engine and transmission testing, benches for special applications and upon customer specification.
DYNAS enables a large combination of duty cycles, simulating steady state or dynamic testing of driving systems, based on IC as well as electric motor.
Developed in Labview (National Instruments), DYNAS allows the automatic simulation of the vehicle inertia, the gear change, the transmission power loss and the environmental effects as wind, road, positive and negative slope of the road.
The Data Acquisition and Control system receives all the required data from the field sensors and controls both the dynamometer and the engine under test.
The torque set-point is calculated, moment by moment, by the DYNAS software, as a function of the actual speed value and the road simulation data previously set by the operator, such as:
- vehicle mass
- front section
- wheel’s diameter and inertia
- cx factor

Fig.6, 150 kW dynamometer

The theoretic requested engine torque is generally given by the following formula:

$$Cm = Cp + Cv + Cd + Ca + Ci \qquad (4)$$

where:

Table 2: definitions

Slope Torque	Cp
Rolling friction Torque	Cv
Dynamic Torque	Cd
Drag Torque	Ca
Inertial Torque	Ci

The torque set-point is:

$$Cs=Cm - Je*d\omega/dt \quad (5)$$

Table 3: definitions

Set Torque	Cs
Engine Torque	Cm
Dynamometer inerzia	Je
Engine Angular Acceleration	dω/dt

Fig.7. Twin 30 kW dynamometers

The dynamometer is capable of changing from negative mechanical power (i.e., generating mode) to positive mechanical power (i.e., motoring mode) in order to simulate deceleration, downhill, etc. (normally not requested and not available in a dynamic dynamometer for internal combustion engine). It is therefore possible, Fig.8&9, to set up separately mechanical braking and electric braking (a percentage of the total, depending on the electric storage technology and dimensioning), enabling the study of power flow, regenerative braking, and power stability of the dc bus

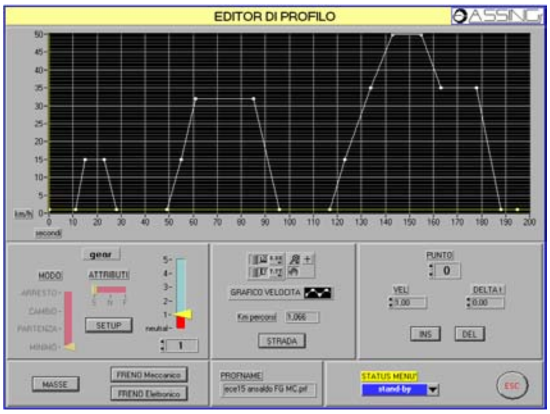

Fig.8, dynamometer set up

The inclusion of the above parameters, editable by the researcher during the set up of the speed profile, makes the ENEA dynamic test bench suitable for the simulation of hybrid and electric vehicles and enables the study of power flow, regenerative braking, and power stability of the DC bus.

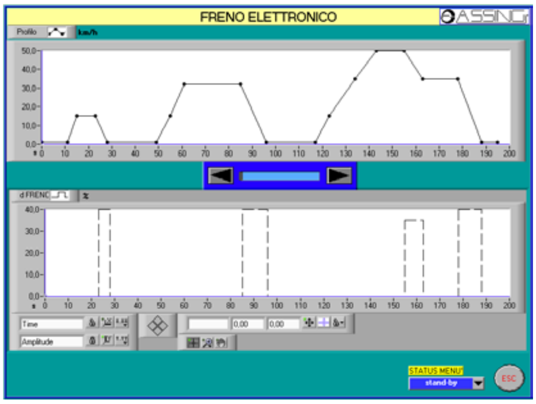

Fig.9, electric braking percentage set up

Each test bench allows a wide combination of duty cycles, simulating steady state or dynamic testing of driving systems.
By using this facility, the behaviours of PEM Fuel Cells of different sizes (7, 15, 22 kW) were simulated by replacing them with a AC/DC converter, controlled by a microprocessor platform that regulates the output voltage of the FC emulator as a function

- of the output DC current
- and working temperature.

This fuel cell emulator powered a full scale hybrid drive train, based on a 30 kW electric motor coupled to the dynamometer, plus a battery pack.

4 A HIL testing campaign of a real FC power system

Two testing campaigns were performed, the first one in Turin by CRF (the Fiat Research Center), and the other in Rome by ENEA and the University "ROMA TRE" [10].

Fig. 10, the real 60 kW FC at CRF in Turin

In Turin a real hybrid 60-kW FC powertrain was tested, Fig.10, the obtained results were used to build the control function for the FC emulator and to validate the results from the power train being tested in Rome.
The fuel cell emulator maximum power was scaled down to 7, 15, 22 kW.
The test was aimed at verifying control strategies, on the same mission, for vehicle with a different hybridization degree, at different battery state of charge.

4.1 Experimental lay-out

Figs. 11 & 12 (at the end of the paper) show the layout of the real FC powertrain tested in Turin and the emulated FC arrangement tested in Rome, respectively. Fig. 13 shows the real arrangements of the hardware in the ENEA laboratories.
A Multi Input Power Electronic Converter (MIPEC), jointly developed by ENEA and University ROMA TRE [11] [12], feeds the traction drive and manages the power flowing from different sources (up to three) , in this case the battery pack and the FC emulator. In the MIPEC the IGBT duty cycles are controlled in order to meet the power demand of the traction drive. In doing that, the MIPEC control manager provides sharing among the two power sources of the power flow being on demand. Such a control strategy is accomplished by taking into account the battery states of charge (SOC), as well as both the maximum admissible power flow variation and the efficiency map for each power source.

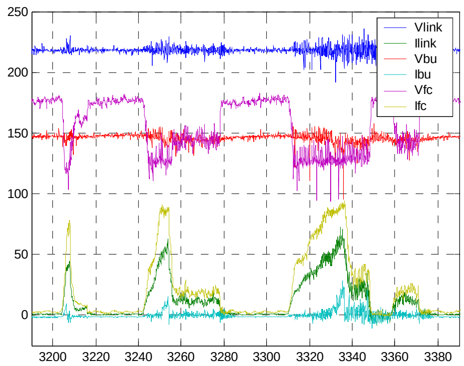

Fig.14. Power flow sharing over one urban cycle

The FC emulator has been accomplished by means of a AC/DC 3-phase converter and a suitable DC link capacitive filter. A microprocessor platform based on x86 architecture regulates the output voltage of the FC emulator as a function of the output DC current and working temperature The microprocessor behaves on the basis of a detailed FC model, the FC model being compiled through Matlab xPC Target; at given FC generated current the instantaneous output voltage level can differ depending on the operating conditions, as shown in , Fig.14.
The traction drive is coupled to the four-quadrant operation dynamometer, that can be controlled for generating any driving schedule. A hypothetical city car with a total mass of 1350 kg and provided with our “fuel-cell-powered” drivetrain has been tested over various driving cycles. All the relevant parameters for the vehicle characterisation were derived from the Fiat 600 Elettra tested in ENEA, which was equipped with the same electric motor we tested on the bench. In particular we used for comparative tests the European homologation cycle NEDC, Fig.16, while for the driveability test the American UDDS, Fig.17, was used.

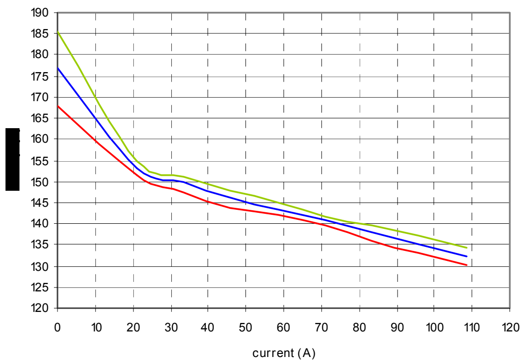

Fig.15, FC emulator voltage vs. current profile1

Moreover, since in the past the same Fiat 600 Elettra was already tested on our roller bench, it has been possible to validate the results obtained during current testing. The sensors data have been acquired with a time step of 0.1 s in Matlab®/Simulink environment, 1 upper and lower curves correspond to maximum measured scattering thanks to real time ADC boards of Diamond Systems Corporation.
Hydrogen consumption and system efficiency have been calculated thanks to the fuel cell emulator and the energy flow management carried out in real time. Just like in the actual fuel cell operating in Turin, the power supplied by the fuel cell emulator is not affected by the power consumption of fuel cell and vehicle accessory loads. In the pictures below two of the used tests profile are shown:

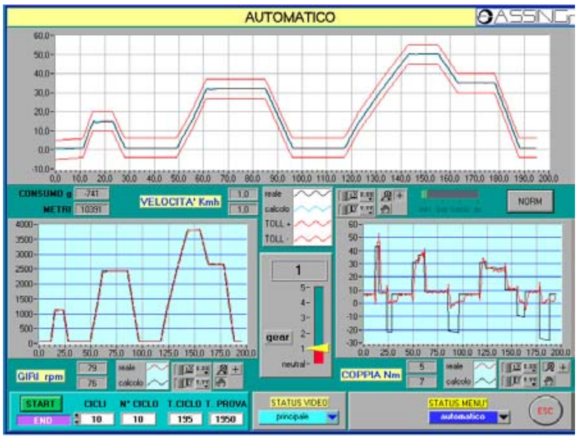

Fig.16. Testing of the powertrain over one urban section of the New European Driving Cycle

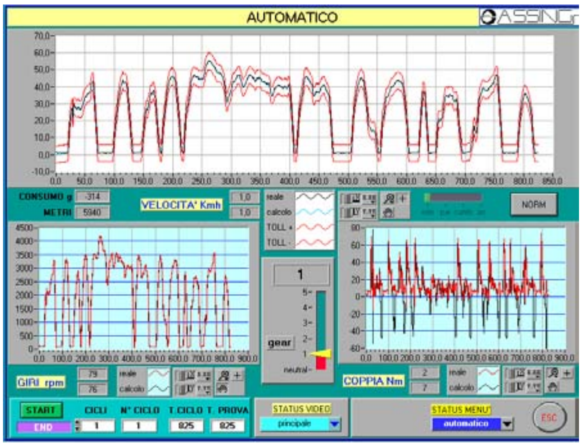

Fig.17, testing of the powertrain over a section of the U.S. UDDS

Preliminary tests showed that the rate of the currents supplied by the fuel cell emulator was always bounded inside a foreseen narrow range and the "fuel cell" had not to feed the traction power rapid variations.
This result may be achieved because the MIPEC converter can split up accurately the power request from the traction drive between the fuel cell and the battery pack. The batteries must supply the peak power request over the cycle and the fuel cell provides the mean power.

4.2 Experimental matrix

A number of tests have been carried out for measuring the fuel (hydrogen) consumption with different drive train and different battery SOC.
The operating conditions and parameters considered in this activity were (Table 1):
• a decreasing of the battery state of charge (SOC) initial values, which corresponds to an increasing initial ability of battery recharging – e.g. ability of storing electrical energy when the vehicle is braking;
• the behaviour of fuel cells of increasing sizes, by increasing the maximum current the fuel cell system can provide.
By this way, powertrains with increasing hybridization ratio have been investigated.
Each test lasted approximately one hour, to reduce the weight of errors in SOC assessment by increasing the absolute values of input/output energy throughout the battery. During each test a set of parameters were measured, recorded and elaborated:
• Motor speed and corresponding travelled distance;
• FC generator, battery and electric motor currents and voltages.
The difference between total battery input and total battery output corresponds to battery losses.

Table 4: Experimental matrix

Fuel cell system maximum power	HD	SOC: 0.8	SOC: 0.6	SOC: 0.4
7 kW	0,23	Test N. 1	Test N. 4	Test N. 7
15 kW	0,50	Test N. 2	Test N. 5	Test N. 8
22 kW	0,73	Test N. 3	Test N. 6	Test N. 9

4.3 Experimental results

The table below shows the main results achieved from the carried out testing activity.
To better understand the data reported above, referring e.g. to test Nr. 5, we have:
• in Fig. 18, an intuitive scheme shows the mean power flows (Watts), measured during the Test;
• in Fig. 19, the acquired data over 20 consecutive ECE 15 cycles, with a total duration of 4000 s;

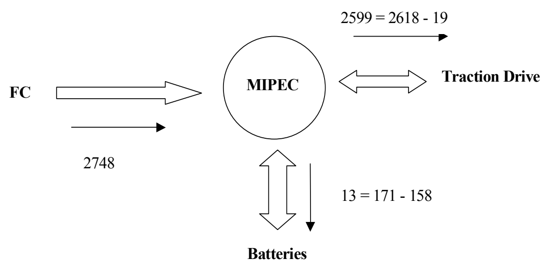

Fig.18. Mean Power Flows over 20 ECE-15 cycles (Watts)

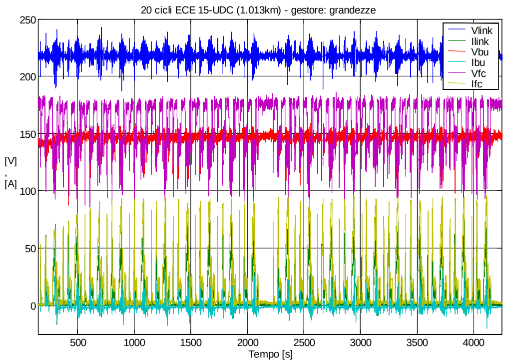

Fig.19. Measures acquired over test nr. 5

It is a detailed zoom on a single ECE 15: the top trace is the link voltage (Vlink), that is maintained constant thanks to the MIPEC; below we have battery and FC voltages (Vbu & Vfc), and, at the bottom of the figure, the three currents (Ilink, Ibu, Ifc):

Fig.19. Zoom related to a single ECE 15

The mean specific electrical power measured at the traction drive terminals, which accounts for the
regenerative power too, is 2.17 kW/ton. The specific consumption is 106 Wh/ton km. This datum meets the specific consumption measured on the roll test bench, 100Wh/ton km. This result shows that the introduced assumptions do not affect the testing activity, and we are trustful that we can also extend other considerations to the real case. The mean hydrogen consumption over 20 ECE 15 cycles is 154 grams, that means a specific consumption of 209 Wh/Ton km. Therefore the mean efficiency of this HEV powertrain is 51%.

4.3.1 How the battery SOC affects the fuel consumption

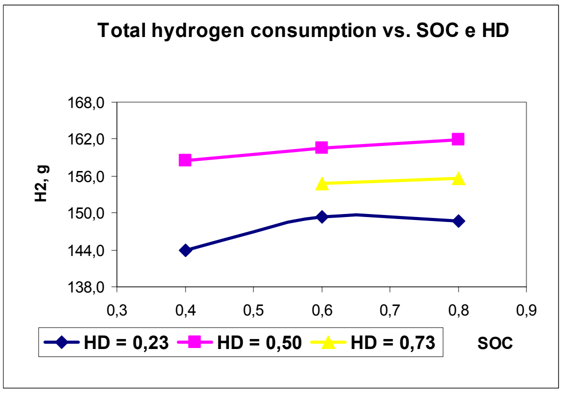

Fig.20. Hydrogen consumption vs. SOC at 3 different HD

Fig. 20 shows the hydrogen consumption in various tests, for different SOC and fuel cell sizes: Obviously, owing to the braking energy recovery, the initial batteries state of charge affects the total consumption. This is the reason because the energy generated over the cycles by the fuel cell is lower if the initial SOC is lower (see Fig. 21).

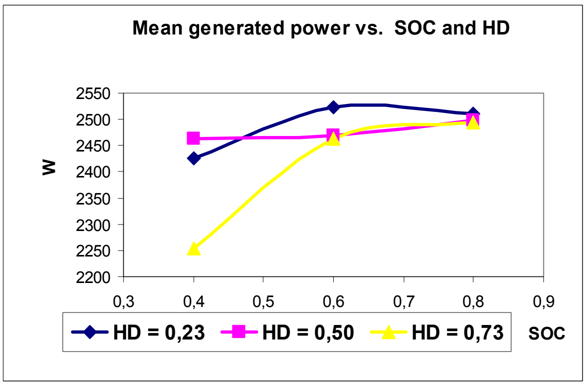

Fig.21. Mean generated power vs. SOC at 3 different HD

The regenerative energy doesn't seem to affect very much these results in propulsion systems with lower hybridization ratio (fuel converter of lower size), but such a conclusion should be a mistake. In fact, the used battery pack – composed by 18 Genesis 12V/13 Ah - is always the same in the three powertrains, and only the fuel cell power is resized in each test

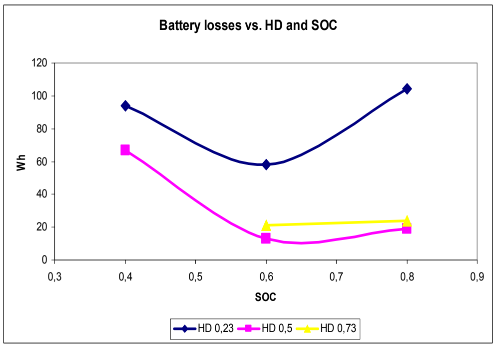

Fig.22. Battery power loss vs. SOC, at 3 HD values

On the contrary, if we want to downsize the fuel cell in a real vehicle, it needs to increase size, capacity and mass of the batteries, and their internal resistance and power loss should decrease. Therefore, when the fuel cell power size is low (7 kW and 15 kW), the battery pack in the test bench is probably undersized. In fact, the batteries power loss vs. SOC and HD (Fig. 22) shows the tendency of a decreasing battery loss at increasing fuel cell power. Minimum values, for every HD, are around

SOC = 0,5-0,6, where battery internal resistance is lower.

4.3.2 How the Hybridization Degree affects the fuel consumption

In spite of higher battery losses [1], the total hydrogen consumption is lower with the smaller fuel cell, Fig.23, because the distribution of operating points of the fuel cell can be more favourably compared to the efficiency plot of the fuel cell system vs. the fuel cell operating points, Fig.24, 25 at the end of the paper, refer to a fuel cell power of 7 kW and 22 kW, respectively

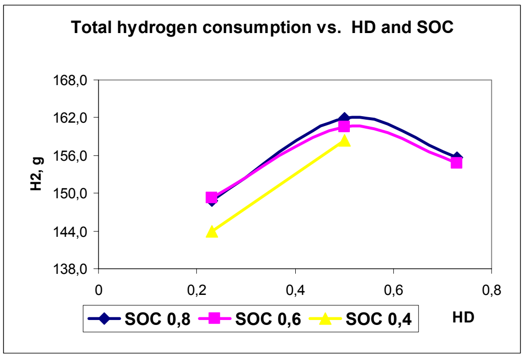

Fig.23. Hydrogen consumption vs. hybridisation degree at 3 different SOC values

The smaller fuel cell has to recharge more often the batteries, which provide most of the acceleration power and are discharged. Nonetheless the fuel cell thus operates mostly in its high efficiency region, and although it generates more energy than the 22-kW fuel cell (Fig. 21), its total hydrogen consumption is lower (Fig. 23).
Finally, by this way the batteries operate in the medium-low SOC range with reduced losses and high regenerative braking efficiency.

5 Conclusions

The results of the experimental test campaign demonstrated:
• the advantages to use HIL testing in the power train design
• the feature of a FC emulator to characterize a fuel-cell-propelled drivetrain
As a matter of fact, in this way it has been possible:
• to take into account real battery efficiency curves and their effect on fuel economy
• to simulate the behaviours of PEM Fuel Cells of different sizes (7, 15, 22 kW), operating at different batteries State-of- Charge.
Considering the urban section - ECE 15 - of the New European Driving Cycle (NEDC), the best design – with lowest fuel consumption - of a hypothetical small city car is a range-extender, i.e. a hybrid vehicle with a very low hybrisation degree (HD = 0,23), Fig. 1 at the end. In case of a more severe driving cycle, the optimal HD probably would be higher, therefore the real problem is to verify if it is possible to define a “real world” driving cycle for the vehicle whose powertrain we are called to design.

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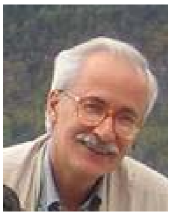

Since 1990 **Giovanni Pede** has worked in ENEA testing laboratories for vehicles and automotive components like motors, traction batteries, supercapacitors etc. at the Research Center “ La Casaccia”, near Rome. He is author of more than 60 papers, about traction systems design and automative components innovation, published on international congresses and scientific journals.

Angelo Puccetti has been with ENEA since 1984. He has worked as Scientific Employee on industrial energy management and environmental impact. From 1997 on his interests are in advanced hybrid powertrains, automatic transmissions for hybrid vehicles and innovative energy storage systems.

Ennio Rossi joined ENEA in June 1984 and since 1994 he is involved in electric and hybrid vehicles testing, carrying out test results on scooters, cars and light commercial vehicles. At the moment, he is responsible of a number of programs for hybrid vehicles prototyping.

Since 1996 Luca Solero has been with the Department of Mechanical and Industrial Engineering, University ROMA TRE where he currently is an Associate Professor. His research interests include power converter topologies, permanent magnet motor drive and control systems design for unconventional applications such as electric and hybrid vehicle and renewable energy systems. Mr. Solero is a member of the IEEE Power Electronics and IEEE Industrial Electronics Societies.

Alessandro Lidozzi received the Electronic Engineering degree from the University of Rome “ROMA TRE,” Rome, Italy, in 2003. In 2007 he received the PhD degree in Mechanical and Industrial Engineering from University of “ROMA TRE”. His research interests are mainly focused in multi-converter based applications, dc-dc power converters modeling and control, and non-linear control of permanent magnet motor drives. In 2004 he won a Student Award and a Travel Grant at ISIE – International Symposium on Industrial Electronics. During 2005-2006 he was Visiting Scholar at the Center for Power Electronics Systems (CPES), Virginia Polytechnic Institute and State University, Blacksburg (VA).

Amedeo Morrone is Technical Director of the Electronic sector in ASSING S.p.A. , a leading Italian company that provides “turnkey” solutions, plants and automatic control systems for engine and transmission testing.
He has designed and developed in hardware and software the dynamic test bench for the simulation of hybrid and electric vehicles for ENEA Casaccia.

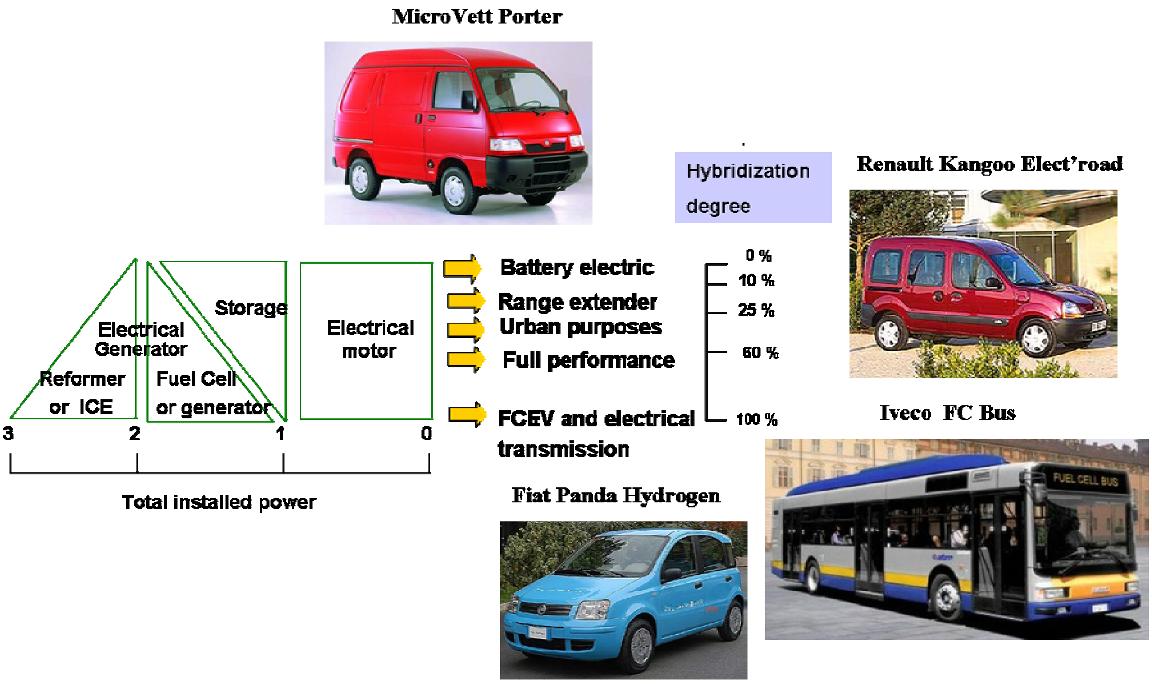

Fig. 1. From top to bottom (clockwise) electric vehicles of increasing HD

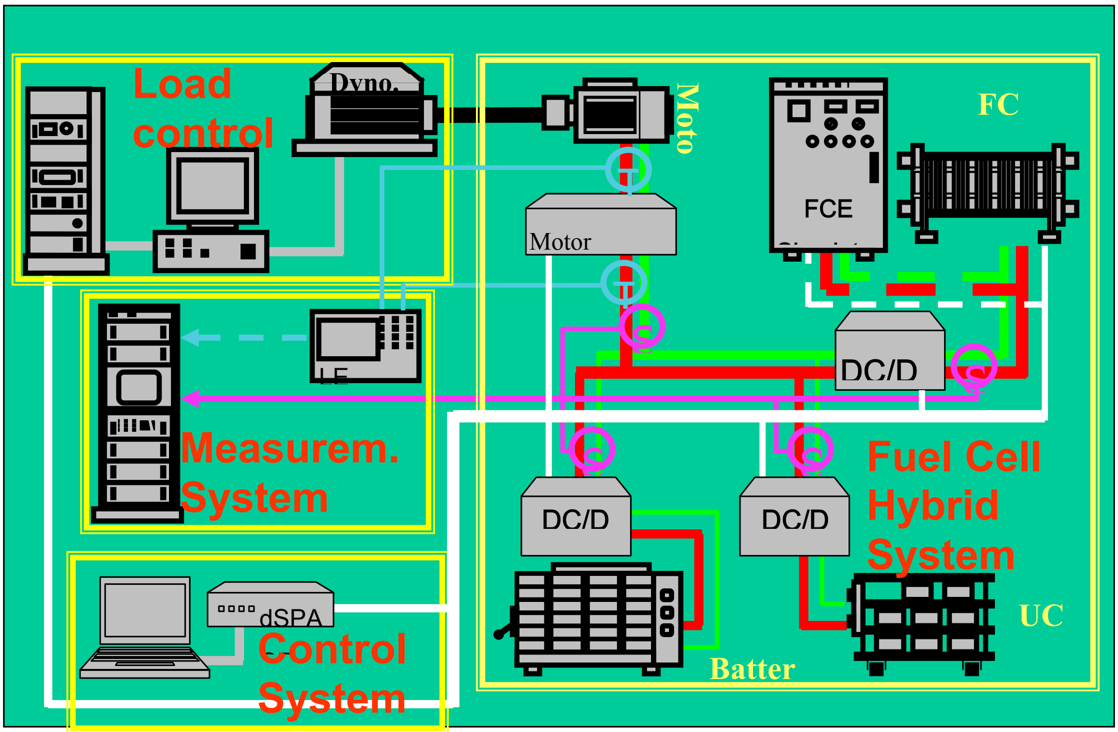

Fig. 3, The Tsinghua University FC vehicle test bench

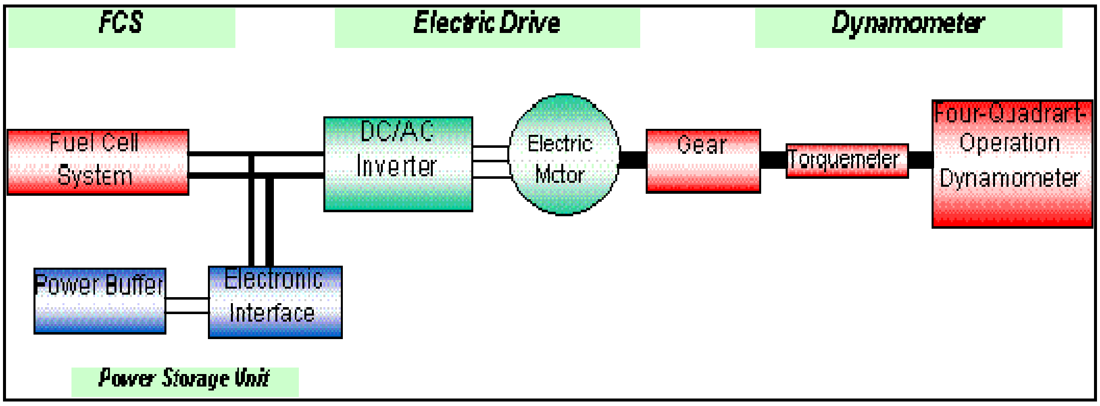

Fig.11. The real FC powertrain layout tested in Turin

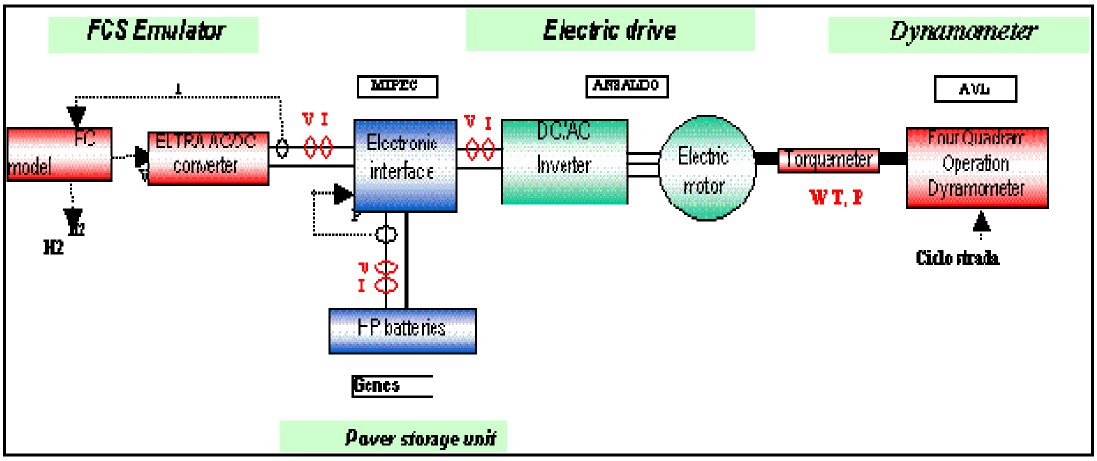

Fig.12. The hybrid powertrain tested in Rome

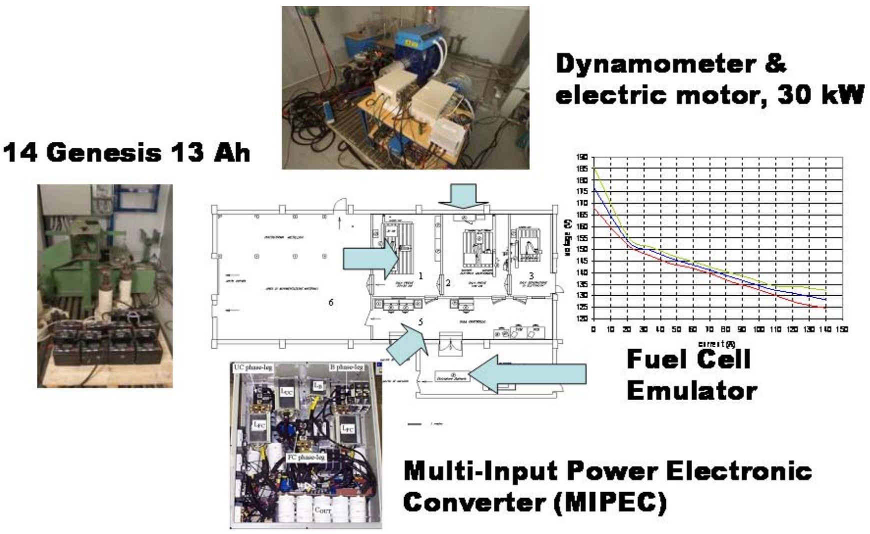

Fig.13 The powertrain layout in the Drive-Train Test facility in ENEA

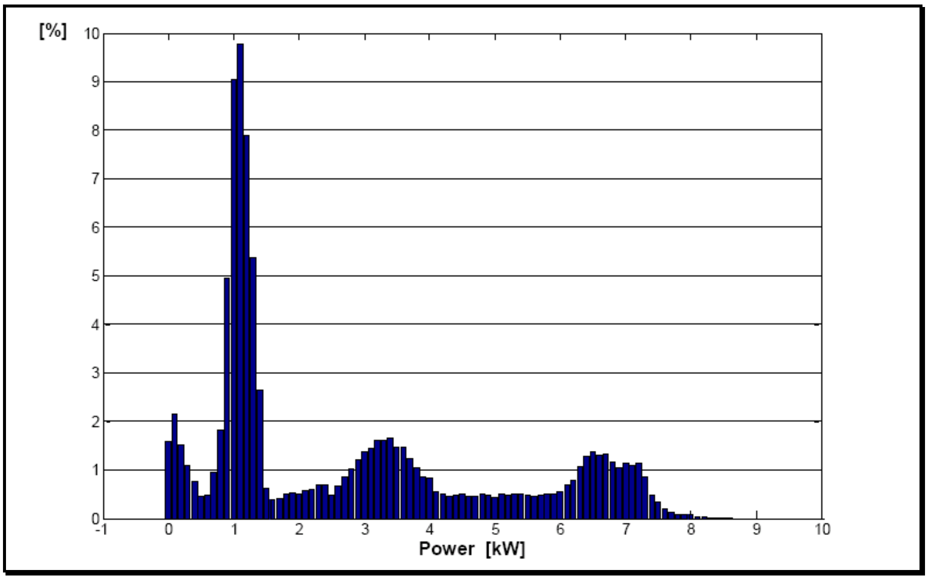

Fig. 24. FC operating points distribution (7 kW, SOC = 0.6)

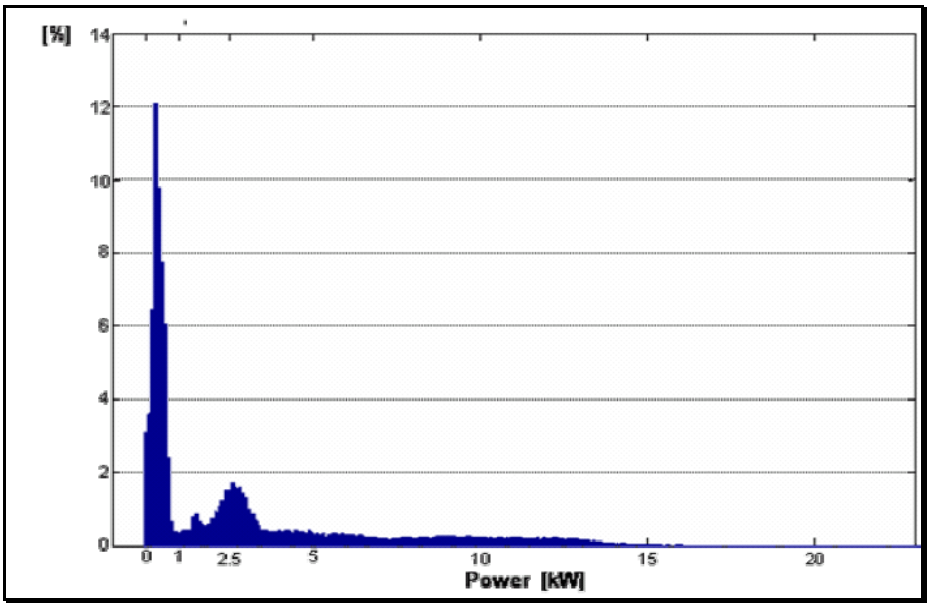

Fig. 25. FC operating points distribution (22 kW, SOC = 0.6)