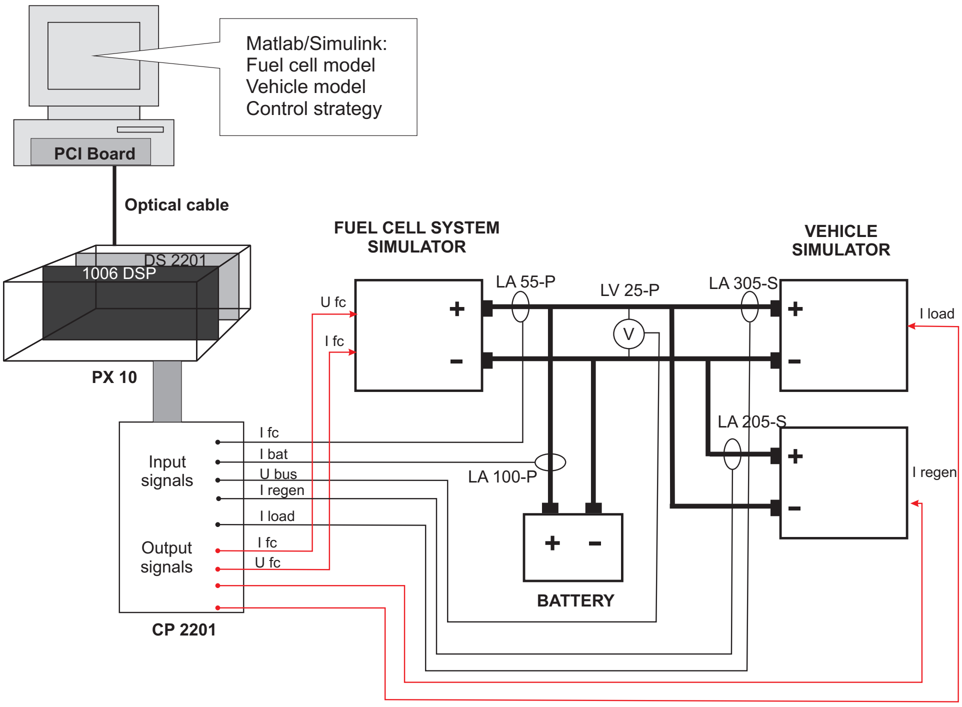

Fig. 7.9: HIL simulation

models, 128 MB of global memory to exchange data with the host computer and 2 MB of flash memory. The I/O boards can be programmed using Matlab/Simulink and Real Time Interface (RTI).

The program developed is executed with a fixed step 1 ms and a fourth order Runge Kutta algorithm. The 1 ms time step selected is smaller than the vehicle (seconds), fuel cell (20 ms for the model used) and battery (10 ms for the battery used) time constant, and can therefore capture the dynamic operation of any system involved. Smaller time steps could lead to heavy experimental data files (e.g. over 1 million samples were recorded for each signal captured during the test carried out.) Figs. 7.9 and 7.10 present the layout and photograph of the whole HIL simulation.

7.4.2.1. Energy management modes (EMM)

In a hybrid system, a wide range of control schemes could be implemented, depending on the objective: maximum range, minimum fuel consumption, minimum *SoC* variation, etc. This wide range of control schemes is due to the hybrid nature of the system, with one source able of supplying

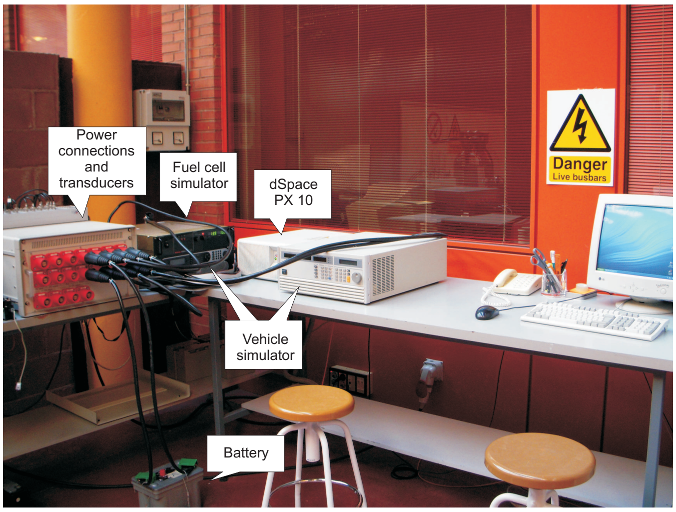

Fig. 7.10: HIL photograph

long term load (fuel cell) and another source capable of supplying shorter term loads (energy storage system). With these different time windows, control schemes may benefit one system but penalize the other. Therefore, some type of compromise should be reached.

In this Thesis, two different and representative EMM of how a control scheme affects each system will be applied: the first one will reduce the hydrogen consumption and efficiently recharge the battery, whilst the second one will keep the battery SoC within an established interval. Of course, other control schemes could be tested.

For EMM 1, the fuel cell output will vary between two different levels (one low level to reduce the fuel consumption and the maximum power point when the load current surpasses 100 A) while supplying the load and recharging the battery with the profile shown in Fig. 7.11. Fig. 7.11 presents this charge profile, in which the values are selected based on previous experiences with the battery.

If the load current is smaller than the rated fuel cell current the battery starts a recharge cycle. The charge current depends on the battery SoC, as for increasing $SoCs$ the battery voltage increases. The recommended charging voltage limit for this battery, as specified by the manufacturer, is 14.4 V. Due to the fact that the charge efficiency decreases dramatically for high

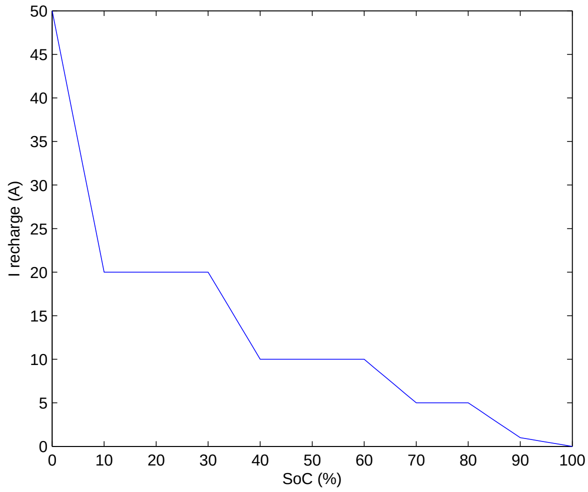

Fig. 7.11: Fuel cell recharge current to the battery

SoCs, the *SoC* is kept between 40 %-60 %, as in this interval there is no risk of overcharge or battery depletion, which would contribute to shorten the battery life due to gasification or sulphatation phenomena. The 60 % upper limit for the *SoC* also assures that the battery will be always ready to accept power peaks during regenerative breaking.

For EMM 2, the fuel cell will be kept at its maximum power point, both during the vehicle power following and during the battery recharge. Hence, the battery will have to deal with the peak transients. If during the driving cycle the battery voltage surpasses the manufacturer recommendation (max. 14.4 V or 1.2 p.u.) the control system will reduce the fuel cell reference (37.78 A or 2 p.u.) in order to reduce the charge regime or force the battery into a discharge cycle, which in both cases will lower the battery voltage.

In general, for both EMMs, depending on the drive cycle, the battery could exceed the maximum 100 % *SoC* if a low load or high regenerative breaking takes place. Hence, if the maximum *SoC* is exceeded the fuel cell reference will be reduced in order to force the battery into a discharge cycle. Also, the fuel cell will be in continuous operation, even during short stops, in order to recharge the battery. However, if the stop time exceeds 5 minutes the control system will stop the fuel cell. Moreover, if during the stop time the battery *SoC* exceeds the 80 %, the fuel cell will also stop.

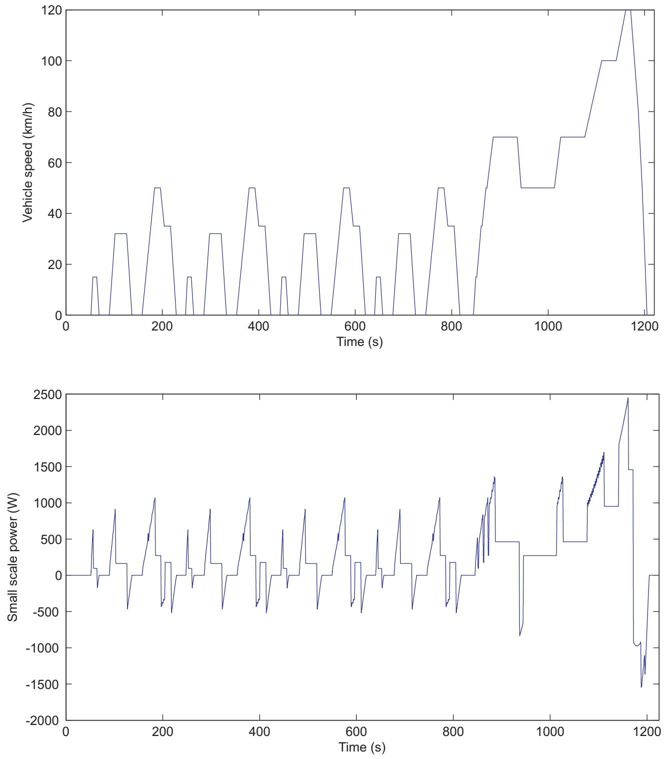

Fig. 7.12: NEDC driving cycle and downsized power (10:1)

7.5. HIL experimental results

To test the p.u. HIL simulation presented, a driving cycle is applied to the simulated system. The New European Driving Cycle (NEDC) simulates during 1225 seconds an urban and suburban route with frequent stops, as it can be seen in Fig. 7.12. The maximum speed is 120 km/h.

With this driving cycle the power requested to the downsized fuel cell/battery system is shown in Fig. 7.12. The maximum downsized power is 2500 W, which corresponds to a real 25 kW of the original application. As the simulation is carried out for a smaller system (10:1), the results presented are expressed in per-unit values.

The simulated fuel cell current is measured by a current transducer at the Sorensen DCS power source which emulates its behavior for both control schemes. The current profile is presented in per-unit values. For EMM 1 in Fig. 7.13 the fuel cell current varies between 1.2 p.u. and 2 p.u., which are the two levels established. There is also a third level at 0.5 p.u., which corresponds to the battery recharge. For EMM 2 in Fig. 7.14 the fuel cell is kept at a constant operation point (its maximum power transfer point), which corresponds with a 2 p.u. current, when the current is referred to the base system. These current values affect the hydrogen consumption, which is 2.5e-3 l/s for EMM1 and 3.7e-3 l/s for EMM2. Due to the fact that this constant operation of the fuel cell will affect the battery SoC and voltage, the control system will measure continuously the battery voltage. It can be observed in Fig. 7.14 that when the measured battery voltage surpasses 14.4 V (1.2 p.u.) the fuel cell current decreases in order to allow a battery discharge or reduce the recharge level. On the other hand, the bus voltage variation for control scheme 1 is lower, as it varies between 0.87 and 1.2 p.u.

For both energy management modes the battery absorbs up to 5 p.u. The battery is recharged both from the fuel cell during low loads or during the regenerative braking. As the battery is reserved for the high peak currents, the bus voltage presents a variation around 1.07 p.u. for EMM 1 and around 1.1 p.u. for EMM 2. The voltage variation is of 0.33 p.u. for EMM 1 and 0.37 p.u. for EMM 2. This voltage variation is a normal situation for a battery, which needs to vary considerably its voltage in order to supply the current demanded during the charge/discharge cycles. This voltage variation is not so dramatic in other energy storage systems. For example, supercapacitors can supply or absorb hundreds of amperes during very short time intervals by just varying mV the supercapacitor voltage.

The battery absorbs the frequent regenerative braking and fuel cell current which keeps the battery SoC. However, the two different energy managements affect the SoC in a considerable way. For EMM 1 the SoC does not vary significantly during most part of the cycle, but collapses during the suburban section. EMM 2 keeps the battery SoC within more appropriate values: 40 % (0.4 p.u.) and 52 % (0.52 p.u.), which avoids the battery depletion or overcharge.

The fuel cell power varies around 2.2 p.u., which corresponds to 550 W in the downsized system and 5.5 kW in the real application. The battery power can reach nearly 5 p.u., which is 1250 W in the downsized system and 12.5

kW in the real system.

7.6. Conclusions

Hardware-in-the-loop simulation is a powerful tool for simulating systems with a high number of components, which may require a complex and expensive setup. In this Thesis, HIL simulation has been applied to a fuel cell/battery hybrid vehicle. Unlike other authors, the vehicle simulation does not include an electric machine to reproduce the regenerative braking. A combined control of a dc electronic load and dc power source allows to simulate both the vehicle power requirement and regenerative braking. This vehicle simulator can easily switch to a stationary load simulator by just changing the programmed power cycle.

The hybrid fuel cell/battery system was setup as a combination of simulated and real hardware systems. The fuel cell simulator can be setup with a programmed dc power source which is able to reproduce the fuel cell voltage and current evolution. On the other hand, the battery is a simple and modular system which can be easily introduced as hardware.

The HIL simulation is carried out under a p.u. system, which allows to downsize the whole test bench and to study the hybridization between simulated fuel cell and battery and was successfully carried out for two different control schemes.

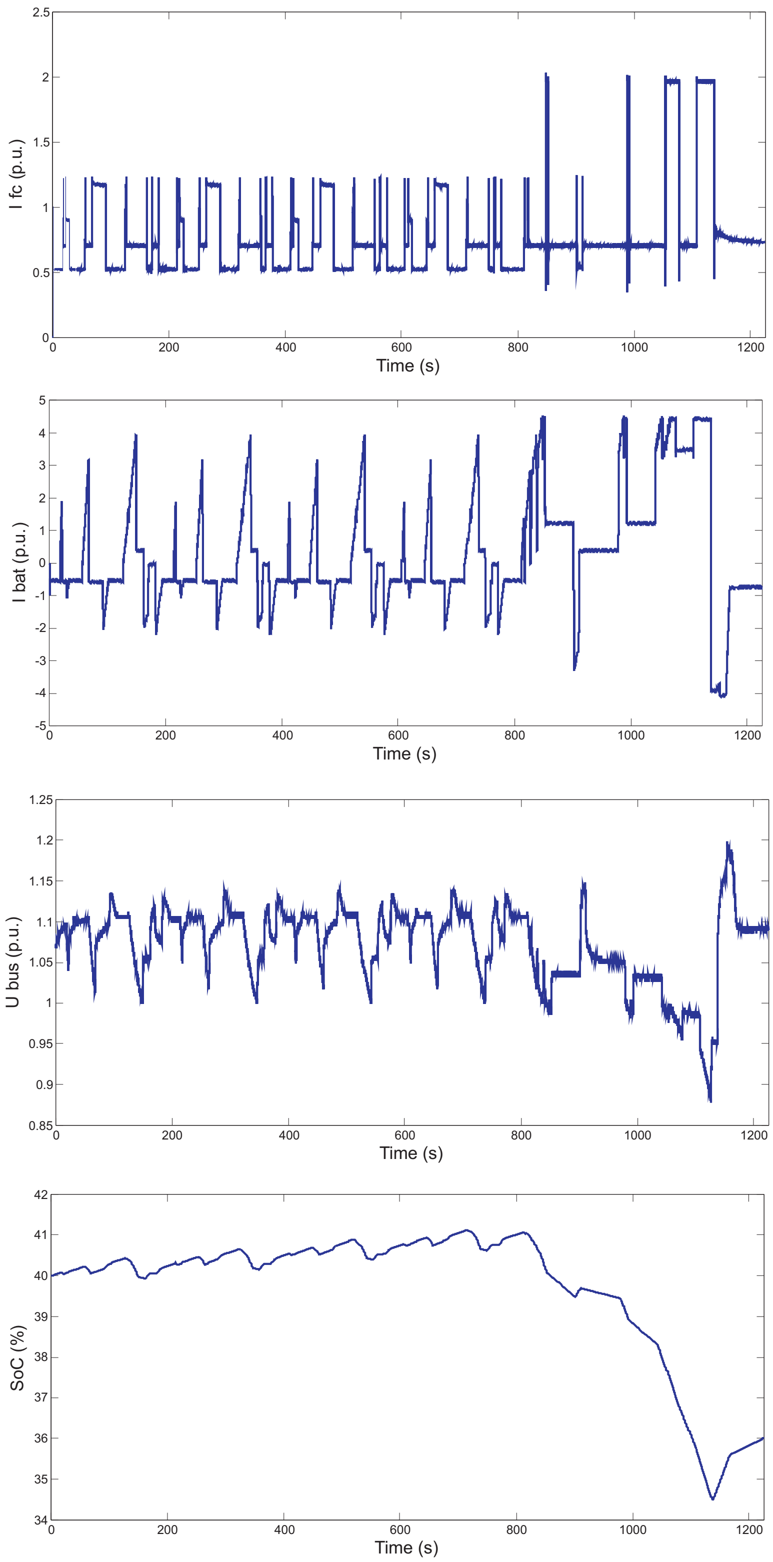

Fig. 7.13: Energy management mode 1

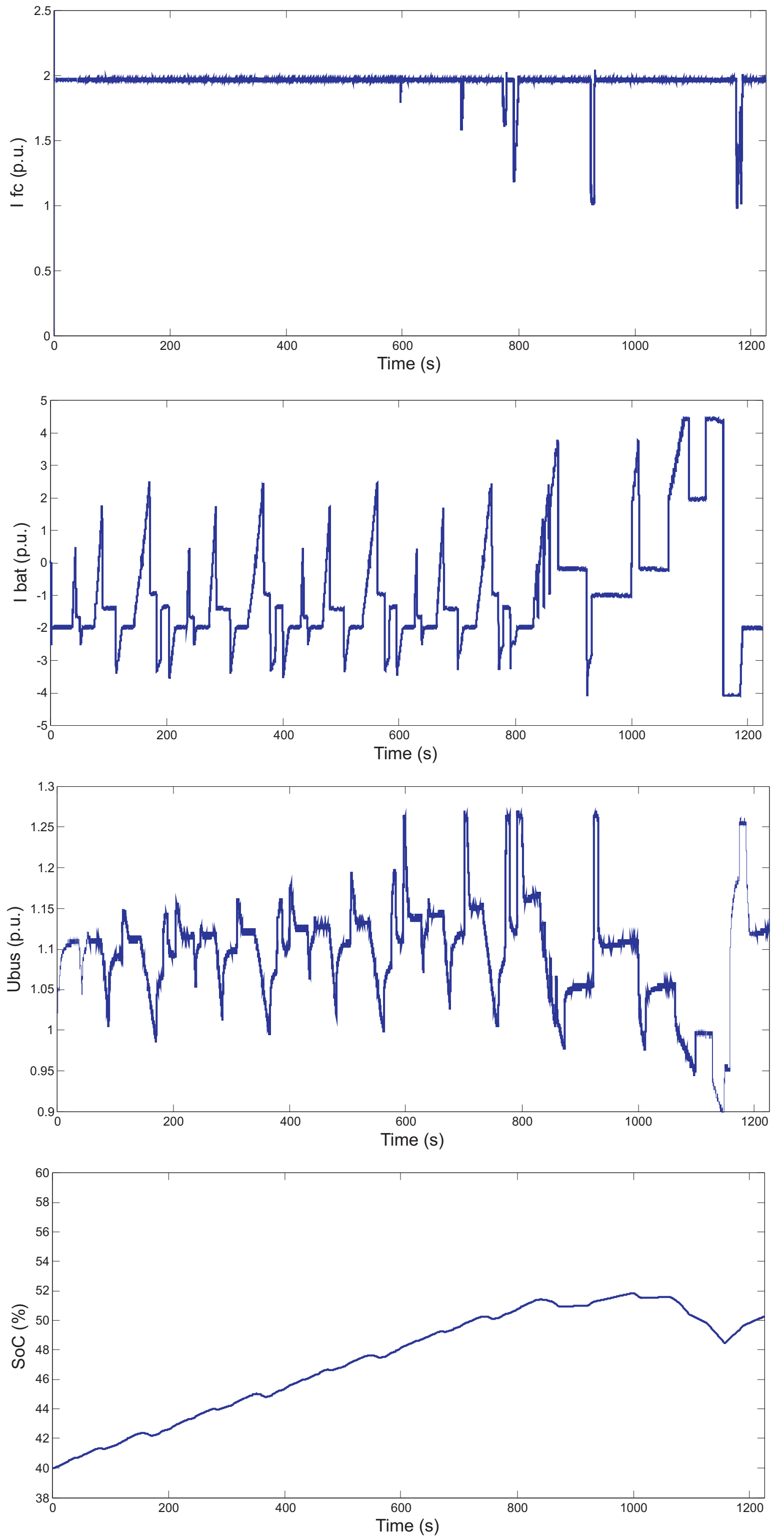

Fig. 7.14: Energy management mode 2

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