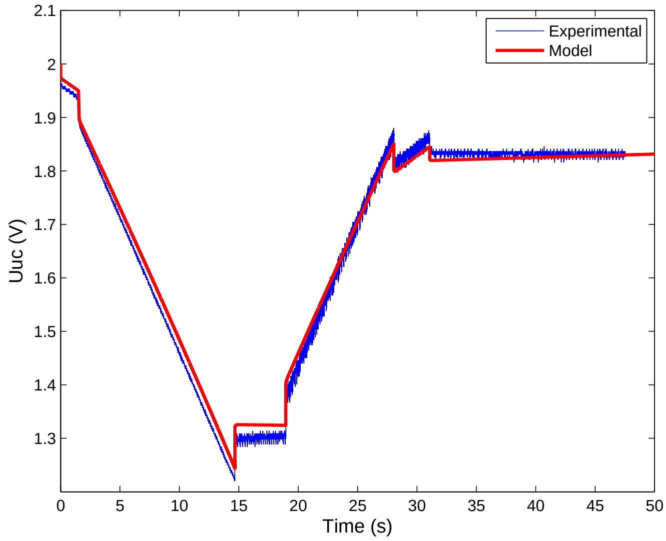

Fig. 6.12: Experimental and modeled voltage

After testing all the equivalent circuits presented by other authors and new ones, the one presented is found to be a good fit for the Nyquist plot and the experimental validation confirms the model adequacy. The model proposed is similar to the one presented by Buller (can be seen in the state-of-the-art chapter), however, Buller included a large number of RC networks, when just the two networks presented render good results. Moreover, the ultracapacitor behavior during high frequencies, not studied or incorrectly explained by other authors, was studied, revealing a reduction of the real part of the impedance due to the pore small effective surface.

CHAPTER 7

HIL simulation for hybrid energy sources

7.1. Introduction

In automotive applications, due to environmental and energetic concerns, fuel cell hybrid electric vehicles (FCHEVs) have turned out to be an interesting alternative to traditional vehicles based on internal combustion engines (ICE). One of the consequences of the development of hybrid electric vehicles (HEVs) is the variety of topologies which the power train can adopt. An overview of these architectures can be consulted in [96]. However, even if FCHEVs present attractive properties, they must still reach competitive achievements in terms of range, cost, fuel storage, etc. To achieve these objectives extensive work must be done in the development and testing of the electrochemical systems (fuel cells, batteries, and ultra capacitors), electric drives, power electronics, and control. The design of some of these subsystems could benefit from adequate tools to lower development costs. This issue is particularly relevant, e.g. during the design of power electronics, when most of the important costs and complexity are associated to the direct connection to the fuel cell system. These design tools can be classified in three groups: pure numerical simulation, pure hardware platforms or hardware-in-the-loop (HIL) simulation systems.

Pure simulation is the most cost effective approach; however the models and simulations carried out are a mere approximation of the real system, and the accuracy of the conclusions strongly rely on the accuracy and validity of the numerical models used. On the other hand, with pure hardware a realistic performance of the devices involved can be obtained [97]. However, this approach presents some drawbacks which cannot be ignored, such as high costs of the elements under test, the infrastructure and security requirements (especially for a hydrogen storage and supply system) and the complexity associated to the performance of the test when a high number of elements are involved.

An intermediate solution between the two previous approaches is the hardware-in-the-loop (HIL) simulation, in which one or several devices of the system are used instead of their simulated models. Depending on the nature of the variables which interact between the simulated and hardware devices, HIL simulation can be classified as signal level, power level or mechanical level, as described by Bouscayrol in [79]. The power or mechanical levels are especially suitable for the simulation of hybrid energy systems in vehicles as the devices involved are power sources, such as fuel cells and batteries, power converters and electric machines.

The HIL test benches presented by other authors [27], [81] include the vehicle simulator as an electric machine working against a brake. But the inclusion of the electric machine and brake results in a high cost and complex HIL system, which is limited to vehicular applications. In addition, these HIL systems could not be used for other power levels as it is designed for a specific case and power rating [98]. If instead of carrying out the simulation in absolute values it is carried out in per-unit values the HIL test bench will be independent of the application power rating.

Hence, obtained the electric models for batteries, fuel cells and ultracapacitors, it is possible to carry out a per-unit HIL simulation of a hybrid system which includes two or more of these electrochemical sources. The HIL test bench developed is able to reproduce a wide range of power applications. Moreover, the vehicle simulator does not consist of any electric machine dri-

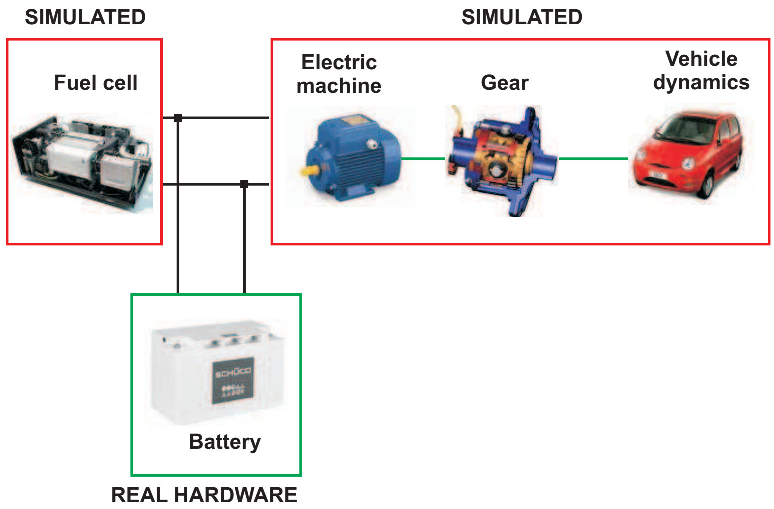

Fig. 7.1: Case studied

ving a break, but of a combined control of a dc electronic load and source, which allows to simulate both the vehicle power requirement and regenerative braking. This simulator does not present the complexity of setup which the electric machine and drive present and is able to follow the vehicle power demand.

7.2. HIL description

The HIL simulation is carried out for a particular case of a vehicular application, as shown in Fig. 7.1.

A vehicle power load profile is formed by a relatively low base power (cruising) with very high abrupt power peak loads (acceleration and overtaking). In vehicles with internal combustion engines, the average power generated by the engine is considerably lower than its maximum power.

If the internal combustion engine is substituted by a hybrid system fuel cell/energy storage, the primary system (fuel cell) can have a lower installed power due to the presence of the energy storage. The fuel cell can supply the power needed for the base power load, however it cannot respond to highly dynamic changes in the instantaneous power load. Fast energy storage devices, such as batteries or ultracapacitors can supply the power requested by the peak loads, but they suffer from serious capacity shortage for the supply of the long term energy [99]. As neither the fuel cell nor the fast energy storage devices can supply individually the whole power load, hybridization between both devices is needed. This is, of course, one of the possible alternatives, but it represents the most essential aspects of the problem. The sealed lead-acid batteries used in Chapter 5 [85], especially designed for traction purposes are used, due to their maturity and robustness, as well as to their ability to supply very high current peaks; however, they may be replaced by ultracapacitors or by other battery technologies [38], such as Ni-Mh or Li-ion, the latter being likely the most frequent choice in the next future.

Once the elements of the hybrid system have been identified two relevant decisions must be made when designing a HIL simulation. The first one is related to which components should be simulated or implemented by hardware. This choice is based on the flexibility, cost and complexity which each system adds to the whole HIL simulation. For example, a fuel cell is a complex and high cost system which needs special environments and installations due to the presence of hydrogen. Therefore, this system is a good candidate for being included as simulated in the HIL system. On the other hand, energy storage systems, such as batteries (or supercapacitors) are modular systems which do not require a specific installation and present a lower cost, simple operation and flexibility. Therefore, they are suitable for being part of the hardware systems in the HIL simulation, especially for electrical or electronic research laboratories, which are not specifically designed to operate with hydrogen-fed systems.

Finally, the load which is fed by the hybrid energy system varies significantly depending on the application (stationary or vehicular). The inclusion of an electric machine and brake limits the application of the HIL platform to vehicular cases and it is a complex and expensive system. Hence, in this Thesis the load is simulated as the parallel connection of a controlled dc electronic load and dc power source. With this load simulation, both stationary and vehicular applications could be simulated, and even regenerative braking can be tested.

The second decision is an important issue related to the sizing of the whole

HIL simulation. The HIL test bench developed should be able to reproduce a wide range of power applications. Therefore, the installed power of the HIL test bench should be high enough to ensure a realistic simulation, but not so high so as to increase significantly the cost and complexity of the setup. In order to satisfy these requirements, in this Thesis we propose a per-unit HIL simulation which is detailed in the following section.

7.2.1. Per-unit HIL simulation

To cope with systems where different currents, powers and voltage levels are involved, power engineers make an extensive use of the per unit system (p.u.). Any system attributes, as dynamic models, control, setup, results and conclusions expressed in p.u. values are also valid for absolute values, as the adimensional magnitudes are linked to the same set of equations (whether static, dynamic, linear or nonlinear) that describe the model behavior in absolute values. Moreover, if the variables are expressed as p.u., the sizing of the HIL test bench can be independent of the real application sizing, and be therefore useful for any power rating.

For the simulated case studied the maximum power rating is 25 kW. As the setup of a 25 kW test bench is more costly and complicated, a smaller test bench with a reducing scale of 10:1 is proposed, which implies a maximum power of 2.5 kW on the HIL simulation. The simulation of this reduced scale system is carried out with the p.u. system, in order to easily extrapolate the results and conclusions obtained to the real power system. The p.u. system will depend on the base values selected. The base values can be arbitrarily decided by the user, however, for the purpose for this work, we have chosen a base power of 250 W, as it is the base power of the power cycle, which will be supplied by the fuel cell. It is proposed to select the battery voltage as the base voltage: 12 V. Known these two values, the base current can be calculated. The following base values have been chosen:
Base power (P_b): 250W.
Base voltage (U_b): 12 V (rated battery voltage).
Base current (I_b): 20.83 A.
Base capacity (C_b): 50 A·h (rated battery capacity).

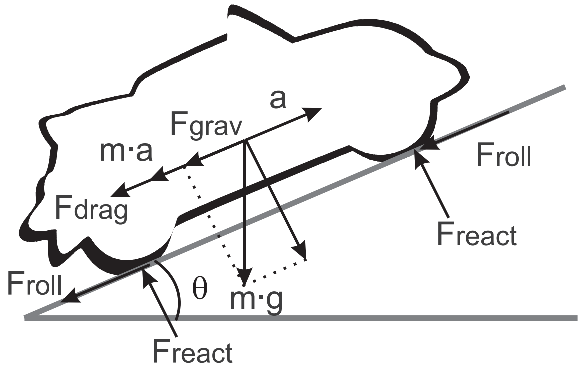

Fig. 7.2: Forces present in a vehicle while driving uphill

7.3. HIL implementation

In this section, we present the HIL implementation for the vehicle model and vehicle and fuel cell simulator. The fuel cell simulator will be based on the dynamic nonlinear model obtained during Chapter 4.

7.3.1. Vehicle model

In this work we use a simplified model for the mechanical part of the vehicle, including vehicle forces, gear box and electric machine. The vehicle power requirements have been calculated through the resistance forces [100] which must be overcome by the vehicle power sources to move the vehicle at the desired speed. These resistance forces are normally calculated while the vehicle is being driven uphill, as shown in Fig. 7.2.

$$\begin{aligned} F_{grav} &= m \cdot g \cdot sen\theta \\ F_a &= m \cdot a \\ F_{drag} &= \frac{1}{2} \cdot \rho_{air} \cdot A \cdot C_d \cdot v^2 \\ F_{roll} &= m \cdot g \cdot \cos\theta \cdot \left(f_0 + f_v \cdot v^2\right) \end{aligned} \tag{7.1}$$

Equation (7.1) shows the resistance forces F_{grav}, F_a, F_{drag}, and F_{roll}. F_{grav} represents the gravitational force, which depends on the vehicle mass m, the gravitational acceleration g and the slope angle θ. F_a represents the acceleration resistance, which depends on the mass m and the vehicle acceleration a. The drag resistance F_{drag} depends on the air density air, the vehicle frontal

Parameter	Symbol	Quantity
Vehicle mass	m (kg)	1000
Frontal surface	A (m^2)	1.8
Drag coefficient	C_d	0.19
Copper losses	k_c	0.3
Iron losses	k_i	0.01
Winding losses	k_w	0.000005
Electronic losses	EL	600

Table 7.1: Parameters for the simulated vehicle

surface A, the drag coefficient C_d and the vehicle speed v. Finally, the rolling resistance F_{roll} depends on the weight $m{\cdot}g$, the slope angle θ , the static friction coefficient f_0 and the dynamic friction coefficient f_v. The parameters for the simulated case are presented in Table 7.1.

Electric powertrains admit different electric machine technologies, such as induction machine, permanent magnets, switched reluctance, etc. as described by [101]. As this work is focused on the implementation of a flexible test bench which allows both stationary and vehicular applications, the electric machine is taken into account as a system which introduces an efficiency factor (7.2) between the power requested by the vehicle and the power supplied by the fuel cell/battery system, centering the attention on the energy sources dynamic behavior and time window. In (7.2), T is the torque needed to move the vehicle at the requested speed; ω is the electric machine rotational speed, which depends on the gear ratio, k_c, k_i and k_w represent the copper, iron and windage coefficient losses. The values for these coefficients are detailed in Table 7.1.

$$\eta_{mot} = \frac{T \cdot \omega}{T \cdot \omega + T^2 \cdot k_c + \omega \cdot k_i + \omega^3 \cdot k_\omega + EL} \tag{7.2}$$

7.3.2. Vehicle simulator

The vehicle simulator is implemented by means of a programmable dc electronic load and a dc power source, operating under combined control mode, similar to the one used during the ultracapacitor testing. The dc electronic load (Chroma 63201) acts as a sink for the power generated by the energy sources, whilst the dc power source (Sorensen SGI) can generate regenerative braking by injecting power to the dc bus to which the energy sources are connected. It is important to take the regenerative braking into account as it has an important impact on the battery state of charge SoC and the vehicle range due to the recharging cycles.

One of the advantages of this vehicle simulator, compared to the one used by other authors, is that it presents a lower cost and complexity than an electric machine and brake system. Moreover, it adds flexibility to the whole test bench, as any load power cycle (stationary or vehicular) can be simulated without altering the load simulator. The layout of the vehicle emulator, shown in Fig. 7.3, is composed by a software and hardware simulation of the vehicle. The software part includes the driving cycle, vehicle resistive and tractive forces, gear ratio and electric machine efficiency and torque. Once the speed driving cycle is transformed to a power or current profile, this profile is used to control externally both the electronic load and power source. The control of both the electronic load and power source is done analogically; through a 0-10 V signal which programs the equipment from 0-100 % of its rated value. The power generated by the simulated fuel cell and the physical battery is absorbed by the electronic load according to the programmed power cycle. The dc power source of the load simulator will only inject power in the dc bus during regenerative braking peaks. This power is used to recharge the battery. The power source is protected with a power diode which prevents current from sinking to the power source. The communication between the software and hardware part of the load simulator is done in real-time, as explained later.

7.3.3. Fuel cell simulator

The fuel cell simulator is based on the dynamic nonlinear model obtained previously, which is fed to a dc power source which emulates its behavior. The fuel cell system simulator is formed by a programmable dc power source (Sorensen DCS20-150E) which is programmed with a 0-10 V signal for the output voltage and with a 0-10 V signal for the output current limit, allowing the voltage and current control of the fuel cell, just as it happens when the fuel cell is connected to a dc-dc power converter. These values are establis-

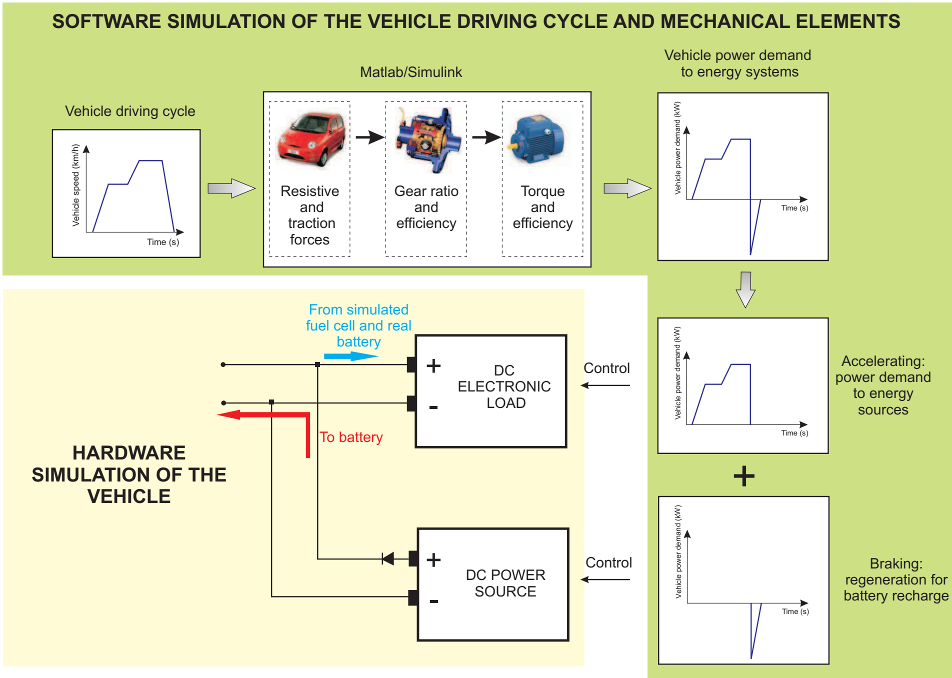

Fig. 7.3: Vehicle simulator proposed

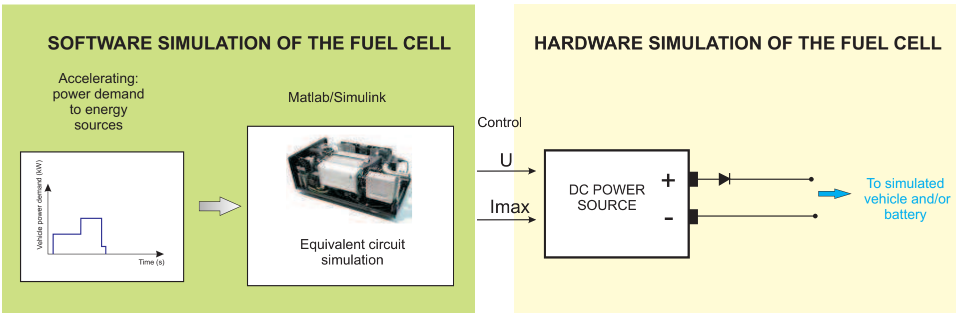

Fig. 7.4: Fuel cell simulator proposed

hed by the control system, depending on the vehicle driving cycle and the battery state of charge, as explained later. The model presented in previous chapters is implemented in Matlab/Simulink and fed to the dc power source, as shown in Fig. 7.4. Just as in a physical fuel cell system, the power source which simulates the fuel cell operation is protected against sinking currents by a power diode. As in the case of the vehicle simulator, the interaction between the software and hardware simulation of the fuel cell system is done in real-time.

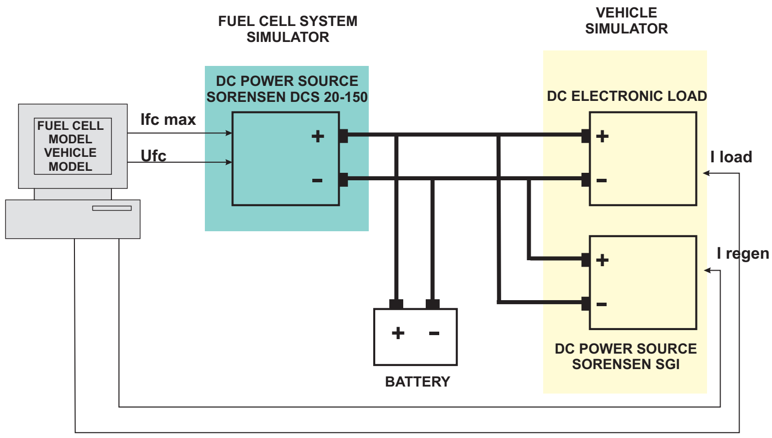

Fig. 7.5: HIL simulation power wiring

7.3.4. HIL power connections

The energy storage subsystem of this hybrid energy application consists of a Maxxima Exide-Tudor sealed lead-acid battery of 12 V, 50 Ah (20 h) connected in parallel to the dc bus. The power connections for the whole test bench are depicted in Fig. 7.5. As it can be observed, multiple power sources are connected in parallel. However, this presents no inconvenience in terms of voltage or current establishment. This is due to two facts. The first one is that the vehicle simulator (dc electronic load + power source) is current controlled, and therefore adapts to the voltage imposed by the hybrid energy system and hence, no ideal voltage sources are directly connected in parallel. The power source which simulates the fuel cell acts as a voltage or current source, depending on the load power requirements. Besides, both the simulated fuel cell and the battery show a non-negligible variable series impedances.

When more than two equipments must be connected in parallel, it is difficult and messy to do it directly. Therefore, for this Thesis we have designed a particular two floor chassis which allows the parallel connection of up to 5 equipments in a safe, direct and neat way. Fig. 7.6 presents the external photograph, which includes safe power connectors (they can endure up to 400 A and 250 V).

An internal power busbar is connected to the Bus, ESS1 (energy storage system 1), ESS2 (energy storage system 2), Power source and Load connectors, so that any equipment connect to these terminals is connected in parallel without having to do it each time the system topology changes.

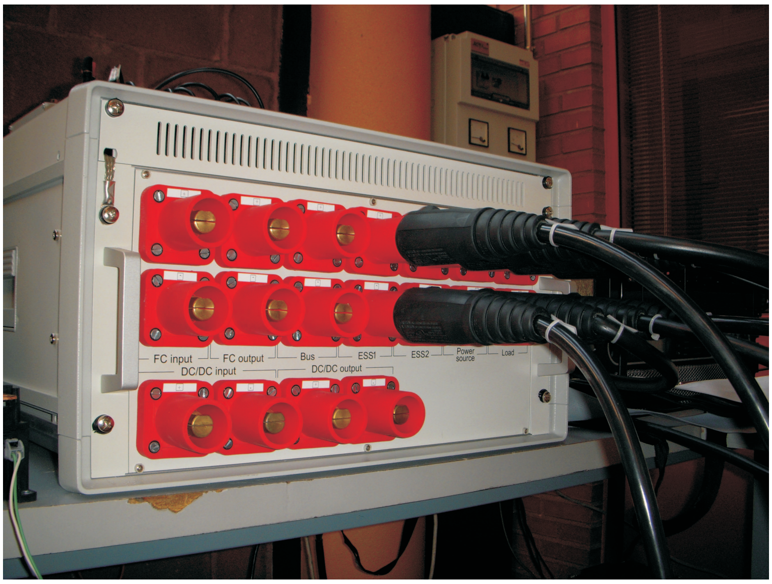

Fig. 7.6: Chassis developed for power connections

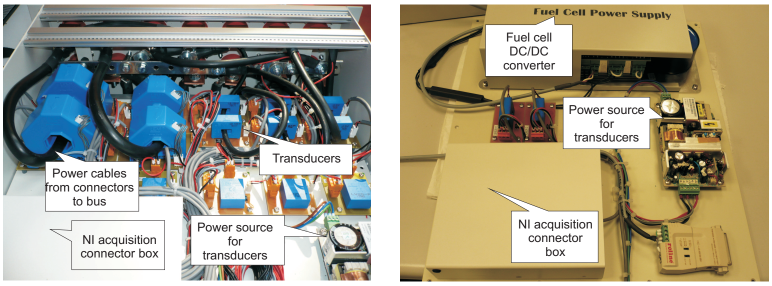

Fig. 7.7: Chassis upper (left) and lower (right) floor

The fuel cell and DC/DC connectors are not in parallel with the rest. This increases the chassis flexibility, because then the fuel cell can be connected to the parallel power busbar either directly or through a DC/DC converter. To connect the fuel cell or the DC/DC converter to the busbar a wildcard connector has been included: the ”Bus” connector. If no fuel cell or DC/DC converter is connected, then it is free to connect a third energy storage system if needed.

As it can be seen in Fig. 7.7 all the transducers are duplicated, in order to acquire with two different acquisition systems (National Instruments and dSpace) and to ensure a reading if one of the transducers fail. Both power and control wiring are included in the chassis, therefore, for safety purposes, a ground connection was included.

7.4. HIL acquisition and control system

7.4.1. HIL acquisition system

An acquisition system is necessary to register the evolution of the different devices involved. LEM transducers are used to measure the dc bus voltage, as well as the simulated fuel cell, dc electronic load and dc power source which emulate the vehicle and battery current. The signals are acquired through an input/output board DS 2201, which is connected to its connector panel CP 2201. Both elements are part of the dSpace real-time control and acquisition system.

7.4.2. HIL control system

Hybrid systems accept a variety of control schemes, as for example [102], [103], [104] or [105]. The objective of the control system presented is to test the HIL test bench, in order to demonstrate its usefulness and applicability.

Due to the fact that the energy system is hybrid between a simulated fuel cell and a physical battery, the control applied in this case will analyze and quantify the power share between the simulated fuel cell system and the real battery. Because the fuel cell system is not able to supply high energy peaks, the fuel cell system will be assigned the role of supplying the average power. With this strategy, the simulated fuel cell can be kept at or near the most efficient operation point. The power peaks will be supplied by the battery, which has a much faster response. The result is the simulated fuel cell feeding the average load power and recharging the battery during low current consumption periods, and the battery supplying power peaks and accepting energy during regenerative braking. Thence, it is possible to have a total control of the hybrid system by what could be called the "energy management mode" (EMM) of the system, which will depend on the type of control selected: fuel cell optimization, battery SoC, etc. The battery SoC at any instant must be calculated (7.3) and controlled.

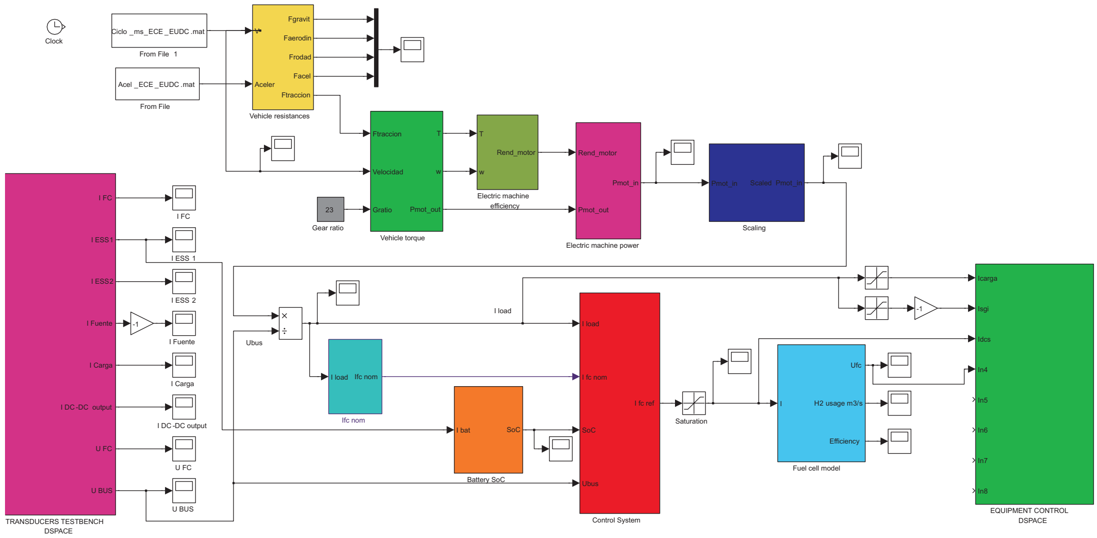

Fig. 7.8: HIL Matlab/Simulink programme

$$SoC_t\,(\%) = SoC_{t-1}\,(\%) \pm \frac{\eta}{C_n} \cdot \int_{t-1}^{t} I(t) \cdot dt \cdot 100 \tag{7.3}$$

The SoC calculation takes into account the charging efficiency and the battery rated capacity C_n. As reflected in the second addend of (7.3), the charged capacity depends on the charge efficiency. The sign of the second addend depends on the battery operation mode: it is positive for charge and negative for discharge.

The complete Matlab/Simulink programme is shown in Fig. 7.8. The control system is implemented in a real-time platform as a general-purpose operating system does not have a consistent, repeatable, and known timing performance. The real-time platform is based on a dSpace Modular Hardware formed by an expansion box PX10, with a digital signal processor DSP DS 1006. The DSP communicates with the host computer through an optical cable and a PCI board. The dSpace and the host computer carry out task sharing, as the dSpace hardware performs the real-time calculation and the host computer provides the user interface and the experiment environment. The DSP DS 1006 is built around an AMD Opteron processor which runs at 3 GHz and has 256 MB as local memory for the execution of real-time