Object oriented model for Plug-In Hybrid Electrical Vehicle

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Nowadays the greatest part of the efforts to meet fuel economy and to reduce pollutant emissions are directed toward the hybridization of automotive drive trains. In particular the design of hybrid vehicles requires a complete system analysis including the control of the energy given from the on board source, the optimization of the electric and electronic devices installed on the vehicle and the design of all the mechanical connection between the different power sources to reach required performances. The aim of this paper is to develop an energetic model for analysis, design and control of a Plug-In Hybrid Electrical Vehicle (PHEV) with particular attention paid to energy and power flux between the different devices. The model described in the following paragraphs has been experimentally validated on a PHEV, realized, in prototypal version, at the Mechanical Department of the Politecnico di Milano.

1 INTRODUCTION

In the last few years, the problem of air pollution has become more and more urgent.

One of the principal causes of this phenomenon is the exponential increase in the number of vehicles with an internal combustion engine (ICE) as propulsor. Indeed, consider that petrol vehicles produce more than a third of the the greenhouse gases emitted in the USA [1]. Naturally this problem involves not only the USA but almost every country in the world. Unfortunately, the pure electric vehicle diffusion is still limited, because its range (generally inferior to 120 km) is still far from a vehicle propelled with an ICE as its main propulsor (generally up to 1000 km) [**?**] [**?**].

In order to join together a wide range and to reduce pollutant emissions a feasible solution is the hybrid electrical vehicle (HEV), which combines, in different ways, an electrical motor to a traditional internal combustion one. For this reason we have continually attempted to the vehicles model to optimize all the additional components and to estimate correctly the power flux and the losses of all the devices installed on board. Furthermore the need of a full extensible model adaptable to any type of vehicle, lead us to realize a fast reconfigurable model through not a few characteristic parameters of the vehicle as the chassiss parameters, the electrical drives ones and the ICEs ones.

In order to study a Plug-In HEV (PHEV) is necessary to develop a complete simulation model. The proposed model, that will be described in the following sections, has been validated on the prototypal vehicle developed by the Mechanical Department of the Politecnico di Milano under a project sponsored by the Regione Lombardia [4, 5].

2 THE PLUG-IN HYBRID ELECTRICAL VEHICLE

First of all a definition of the proposed PHEV is needed. This vehicle can be schematically represented as a parallel HEV, with a system of energy storage over sized with respect to a classical configuration. In this way, the coverage of at least 35 km with a pure electric drive traction at zero emission is guaranteed. The energy for the battery recharge can come directly from the ICE motor or, more efficiently, from the AC net thought a battery charger installed on board.

The construction of the prototype has been based on a standard gasoline vehicle which has been

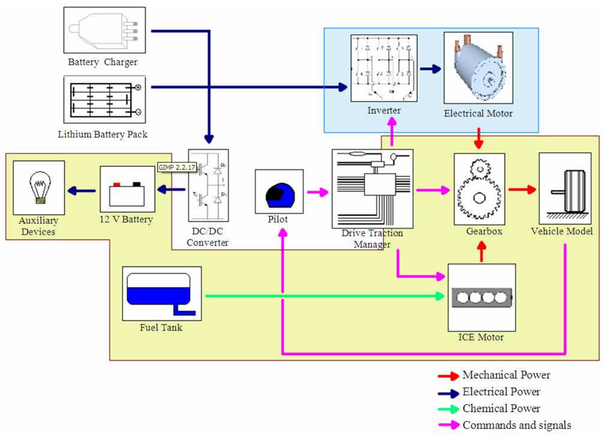


Figure 1: Block diagram of a PHEV

transformed into a PHEV one trying to minimize the number of modifications. Furthermore this type of vehicle gives the driver the choice of the drive traction system. Indeed the possible drive modes are:

- *ICE mode*: the drive power is given from the ICE motor which is supplied by diesel fuel or gasoline. In this mode all the electrical traction devices are turned off.
- *Pure Electric mode*: the drive power is supplied by the electrical motor though the inverter by the battery pack (for example a lithium ion one). The ICE motor is turned off. In this configuration the vehicle becomes a zero emission vehicle (ZEV), with a maximum speed of about 85 km/h with a range of about 35 km, evaluated with an ECE (Economic Commission for Europe Test Cycle) drive cycle and with experimental tests.
- *Start&Stop mode*: in this mode corresponds the vehicle is propelled by the electrical drive traction system up to a speed threshold and above that it is propelled by the ICE motor.

In Fig. 1 the Plug-In hybrid configuration is schematically represented, pointing out the elements that have necessarily been added for the transformation from a conventional vehicles to a PHEV.

3 THE SIMULATION MODEL

The simulation model has been developed using the object oriented approach [2], in fact every single device has been modeled as an object connected to the other ones with input and output information. The objects set represents the whole vehicle model. All the single devices represented in Fig. 1 has been considered: driver, vehicle control system, Li-ion battery, inverter and electric motor, gear box, cluthc, ICE motor, fuel tank, auxiliary on board electrical loads and a longitudinal dynamic of the vehicle. The model has been developed using Matlab/Simulink simulation tool and in Fig. 2 it is shown the main parts of this model. Furthermore in Fig. 2 it is possible to see the main interconnection between the main block that have been developed in order to have a modular structure [8] [3]. In the following sections it will be described the most interesting subsystem of Fig. 2, in particular section 3.2 points the attention on the electrical traction devices, section 3.3 points the attention on the ICE motor, section 3.4 point the attention on the longitudinal vehicle's dynamic and 4 shows the comparison between the experimental data and the results obtained from the simulation imposing to execute the same drive cycle.

3.1 Pilot and drive traction manager

The model receive as input the drive cycle that the vehicle has to execute; this reference is given to a pilot model that gives as output a signal representative of the throttle pedal position. Depending on the mode selected the traction manager splits the request of torque between the ICE and the electrical motor. The drive traction manager also checks, throught maps, that the required torque, both for the electrical and for the ICE motor, is effectively suppliable by the motor. If the torque request exceed the motor limits the drive traction manager provides a reduction as reported in the maps.

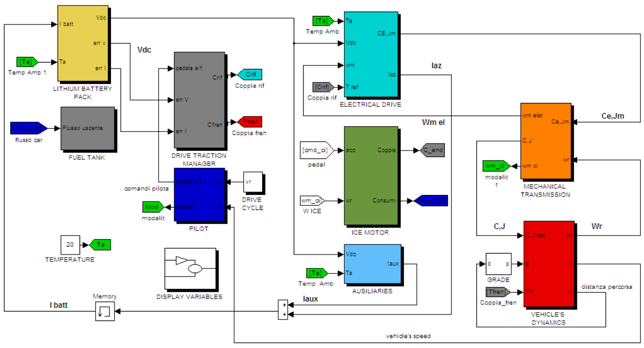


Figure 2: Vehicle's object oriented model

3.2 The model of the electrical drive devices

The necessary devices for the electrical drive traction are substantially the electrical motor, the inverter and the control system. The motor adopted for the prototypal vehicle is a water cooled asynchronous rated of 10 kW; the motor is supplied by an inverter, which is water cooled as well.

The torque requested by the drive traction manager is given as reference to the electrical motor (EM) if the pure electrical mode has been selected. This torque is sent to the EM's model which calculates the operating point as described below.

3.2.1 Electrical motor model

The model of the electrical motor model keeps as input the torque requested from the driver and calculates, known the rotor speed Ω, the phasorial statoric current $\bar{I}_s$ and the phasorial statoric voltage $\bar{V}_s$ that the inverter has to supply to the motor to satisfy the drivers request even if possible.

Furthermore the electrical motor model calculates the power losses using the following parameters: $\bar{I}_s$, $\bar{V}_s$, the power factor $\cos\varphi$ and the rotor speed Ω as described in (1) for $\Omega < \Omega_n$ and in (2) for $\Omega > \Omega_n$.

$$
\begin{aligned}
P_{Cu} &= 3\left(R_s \bar{I}_s^2 + R_r \bar{I}_r^2\right) \\
P_{Fe} &= P_{Fe,n} \frac{\omega}{\omega_n}
\end{aligned}
\tag{1}
$$

$$
\begin{aligned}
P_{Cu} &= 3\left(R_s \bar{I}_s^2 + R_r \bar{I}_r^2\right) \\
P_{Fe} &= P_{Fe,n}\frac{\omega_n}{\omega}
\end{aligned}
\tag{2}
$$

These values are used in the model to evaluate the overall power consumption of the electrical motor, as referred in (3).

$$
P_{EM} = \bar{I}_s \bar{V}_s \cos\varphi \tag{3}
$$

3.2.2 Inverter model

The inverter, represented schematically in Fig. 3, is a traction drive developed for hybrid and pure electrical vehicles. The inverter model keeps as input I_s, V_s, $\cos\varphi$ and ω previously evaluated by the EM's model and calculates the PWM index of modulation necessary to supply the motor with the requested values of voltage and current. If the index of modulation exceed the maximum the inverter limits this value; by this way it is always possible to use the maximum value of voltage available on the DC bus. The inverter model also calculates the power losses of the valves through a energy analysis. As a matter of fact, the switching and the conducting power losses are calculated for each valve both for the transistor (IGBT in this case) and for the diode, as reported in [7]. The synthetic relationship between the and the inverter power losses can be summarized as reported in (4).

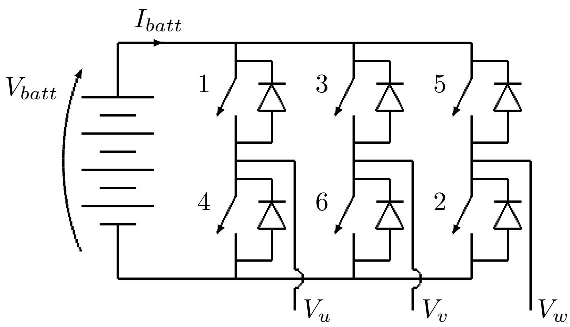


Figure 3: Schematic representation of the IGBT inverter

$$
P_{inv} = P_{inv}\left(V_s, I_s, \cos\varphi, f_{pwm}, \omega\right) \tag{4}
$$

By this analysis it is possible to evaluate correctly the overall current and power required by the inverter to the battery pack, as referred in .

$$
\begin{aligned}
P_{inv} &= P_{EM} + P_{inv} \\
I_{batt} &= \frac{P_{inv}}{V_{batt}}
\end{aligned}
\tag{5}
$$

Finally it is also been added a limitation on the maximum value of current absorbed from the battery: this limitation is necessary to preserve the battery itself in particular to avoid a reduction of its life.

3.2.3 Li-Ion battery pack model

The traction battery pack used for the prototypal vehicle is composed by 60 Li-Co elements with a capacity (C_{batt}) of 50 Ah connected in series. The model of the battery pack aims to validate the model of the single element in order to have a simply extensible model to any battery configuration. The model is energetic and it is comparable to a real voltage generator, as reported in Fig. 4 [6], where all the battery characteristics are function of the state of the element, in particular depend on the State Of Charge (SOC), the temperature (θ) and the sign of the current (charge ch or discharge ds current).

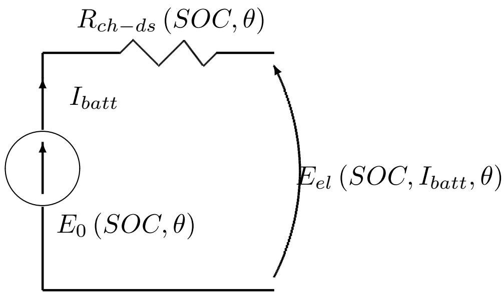


Figure 4: Element's battery electrical model

It is finally possible to give a relationship between the element voltage E_{el} function of the state of the elements itself, as reported in (6).

$$E_{el}\left(SOC,\theta,I_{batt}\right) = E_0\left(SOC,\theta\right) - R_{ch-ds}\left(SOC,\theta\right) I_{batt} \tag{6}$$

The voltage of the whole battery pack V_{batt} is easy valuable by the multiplication of the voltage of each element E_{el} by the number of them. At last the status of charge of the battery pack is valuable by the (7) [6].

$$SOC\left(t\right) = SOC_0 - \frac{\int_{t_0}^{t} I_{batt}\left(t\right) d\tau}{C_{batt}} \tag{7}$$

At the last into the model of the Li-Ion battery pack it has been inserted a first order thermal model to estimate the average temperature of the elements.

3.3 The model of ICE motor

The ICE motor model is based on torque and fuel consumption map. The model has as input the speed of the motor ω_{ICE} and the torque request T_{req} which is given by the driver pilot model. The model give as output the effective torque given by the motor T and the instantaneous fuel consumption of gasoline Φ_{gas}. A schematic representation of this model is shown in Fig. 5.

The maps inserted into the ICE motor block have been obtained experimentally, in particular in Fig. 6(a) it is reproduced the torque map and in Fig. 6(b) it is reproduced the fuel consumption map.

At the last a model of the gearbox has been developed. In particular this model contains the choice of the correct gear to be inserted and a simple model of the clutch action.

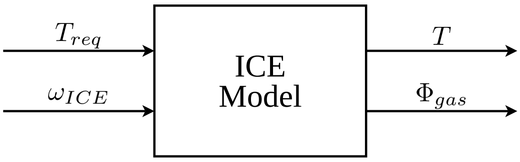
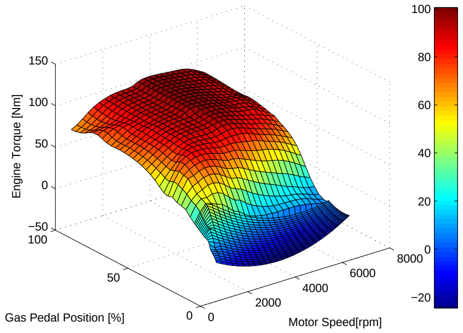
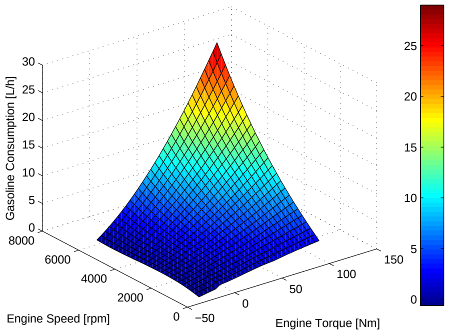


Figure 5: ICE model



(a) Torque map of ICE motor



(b) Gasoline flux map for ICE motor

Figure 6: Maps used for modelling ICE motor

3.4 The model of the vehicle dynamic

The torque produced by the EM and by the ICE meet before of the final gear reduction made by the differential and by the wheel. So the difference between the total force supplied by the two motors and the resistance forces F_{res}, reported in (8), allow to obtain the longitudinal vehicle's acceleration and by its integration the vehicle's speed.

$$F_{res} = m_a a + mgf_v + \frac{1}{2}\rho C_x S v^2 + mg \sin\alpha \tag{8}$$

In equation (8) m_a represents the equivalent inertia of the vehicle, a the longitudinal acceleration, m the mass of the vehicle, g the gravitational acceleration, f_v the rolling friction coefficient, ρ the air density, C_x the penetration coefficient, S the frontal vehicle's area, v the speed of the vehicle and α the grade of the way.

4 VALIDATION OF THE SIMULATION MODEL

Finally, in order to validate the model, different comparison between experimental data and simulation results has been performed. In the following paragraph it is shown the comparison of experimental data and simulation results; in particular paragraph 4.1 refers to the vehicle propelled by the ICE motor, paragraph 4.2 in to the vehicle propelled by the electrical motor and paragraph 4.2 to the vehicle propelled by both the motor used in Start&Stop mode.

The simulation results have been compared with the experimental ones obtained on the prototype where the same drive cycle has been adopted.

4.1 Validation of the model on ICE mode

In order to validate the ICE motor model it is necessary to make a comparison between experimental data and the data given as output from the global model. It has been asked to the model to execute the same experimental drive cycle and shown in Fig. 7 in ICE mode; furthermore, provided that our prototypal vehicle has a manual transmission, it has been said to the model when the driver has changed the gear ratio and when he has pushed the clutch.

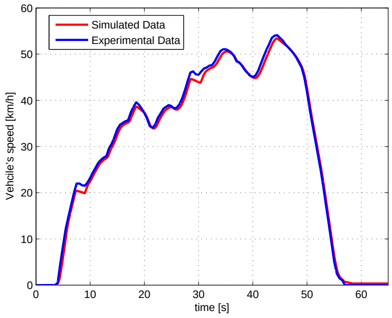
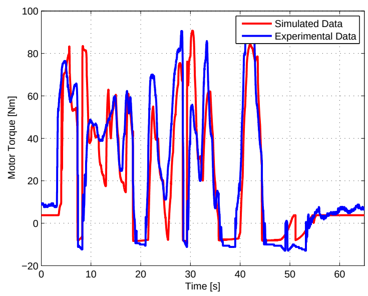
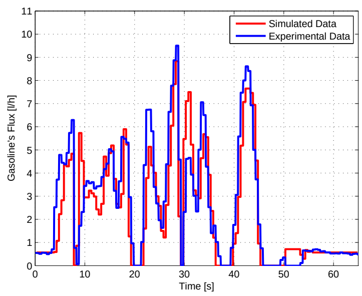


Figure 7: ICE drive mode cycle

In Fig. 8 it is shown a comparison between the torque (a) and the gasoline flux (b) acquired and simulated by the model.



(a) ICE's Torque



(b) ICE's Gasoline Flux

Figure 8: Comparison between experimental and simulated ICE performances

We have to notice that there are some differences between the simulation and the acquired data. In particular the pilot model has to be improved for what concerns the starting from zero speed, in which the clutch effects are non satisfactory simulated. As consequence of this phenomenon we have to notice a little difference of gasoline flux at the start of the vehicle from zero speed.

It is also possible to calculate the cumulative gasoline consumption from the data represented in Fig. 8(b). It has been obtained a consumption of $45ml$ from the experimental data and a consumption of $40ml$ from the simulation. The main cause of the different values obtained in Fig. 8(b) is due to the pilot's clutch pedal action: in fact in experimental data every change of gear ratio is different from the other one and it is very hard to find a general strategy for modeling this phenomenon.

4.2 Validation of the model on pure electric mode

First of all it has been requested to the model to follow the same drive cycle executed using prototypal vehicle during experimental tests in pure electric mode; this drive cycle is reproduced in Fig. 9.

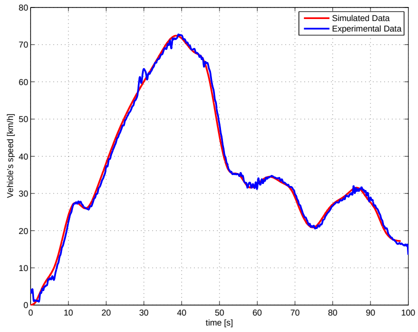
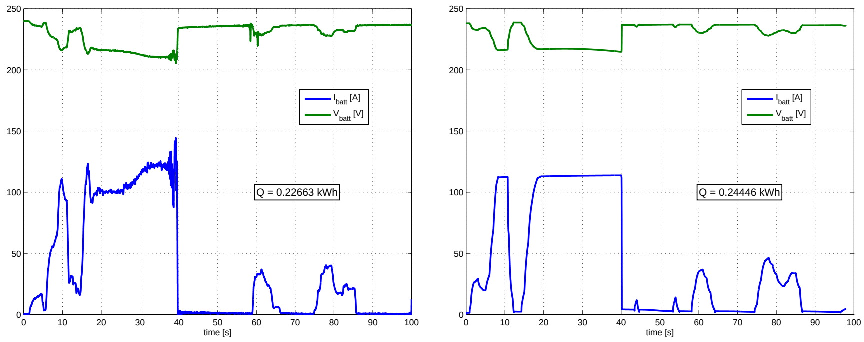


Figure 9: Comparison between the experimental and the simulated electrical mode drive cycle



(a) Experimental data

(b) Simulated data

Figure 10: Comparison between acquired and simulated battery performances

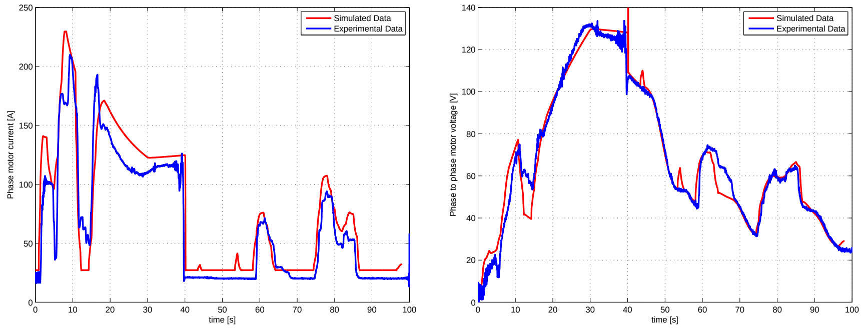
Using the cycle represented in Fig. 9 it is possible to validate the battery performance in terms of voltage available V_{batt} and in terms of current supplied I_{batt}. The comparison between the model performances and the experimental ones is shown in Fig. 10. In the figure over mentioned it is also reported the energy consumption Q evaluated through the acquired data and through the output of the vehicle's model.

The comparison shows a good correspondence between the simulation and experimental data; as consequence the kilometric energy consumption is also well estimated by the model.

Furthermore it is possible to compare the electrical motor performances in terms of phase current and phase to phase voltage, as reported in Fig. 11.

4.3 Validation of the model on Start&Stop mode

At last it has been implemented a Start&Stop strategy on the vehicle. This strategy ask to the electrical drive traction system to propel the vehicle up to a speed threshold set to $32\ ^{\mathrm{km}}/_{\mathrm{h}}$; above this



(a) Motor phase current (b) Motor phase to phase voltage

Figure 11: Comparison between acquired and simulated motor performances

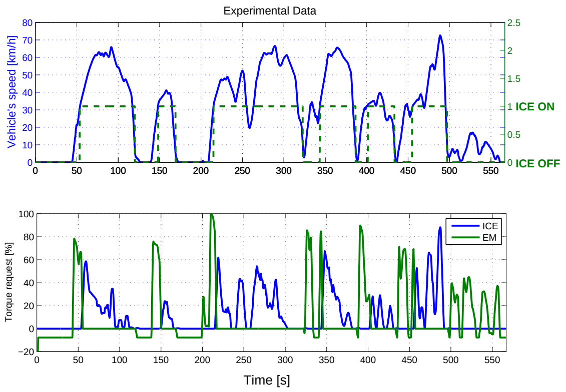


Figure 12: Drive cycle with superimposed the ICE status

speed threshold the vehicle is propelled by the ICE motor. In the upper part of Fig. 12 it is shown the drive cycle used to validate the model in the Start&Stop mode and in the lower part it is shown the torque request repartition between the electrical motor and the ICE motor.

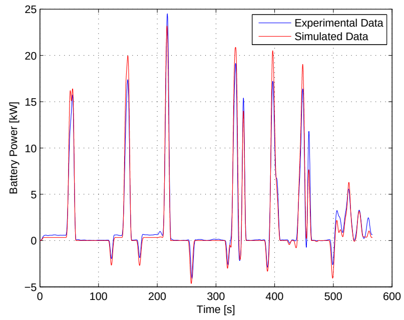
Finally in Fig. 13 it is reported the comparison of experimental data and simulation results obtained using the drive cycle and the strategy reported in Fig. 12.

5 CONCLUSIONS

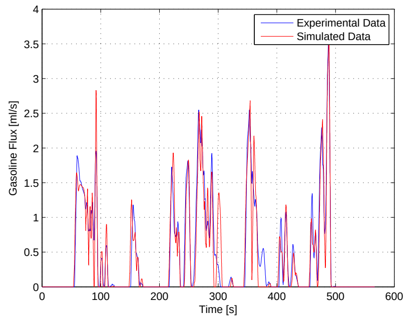
The energetic model over described aims to simulate the overall power flux between the different power trains installed on an PHEV in order to estimate the energy consumption of the vehicle in the different possible modes.

The realized model briefly discussed in this paper is fully scalable to every type of HEV: in fact each component of the drive traction system can be easily redefined by the modification of its sets of parameter. It is also possible a easy reconfiguration of the drive train architecture, for example from parallel to series, acting on the interconnection of the main blocks of the model.

So the model presented can be used as tool for the design of every type of hybrid drive train architecture, in order to accurately predict the performance of the vehicle and the benefits introduced



(a) Battery power



(b) ICE gasoline flux

Figure 13: Comparison between acquired and simulated performances

by the hybrid system, both in term of fuel saved and of pollutant emissions.

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