Control logic for the energetic management for new generation hybrid vehicles

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Abstract

The aim of this paper is to describe the improvement and the steps of the algorithm for the optimal energetic management for the latest generation of hybrid/diesel-electric vehicles. Problems concerning the correct use of the energy chain and the traction control strategy can be solved through real-time measurements of traction system electric parameters using precise and relatively inexpensive acquisition procedures. Theoretically, even if this point of view raises very important practical matters, motor rpm and Power Control seem to be a "closed loop" in order to avoid the employment of consolidated technologies, like the "Kalman filter", which is the result of mathematical equations giving a recursive solution, numerically efficient for the regulation processes. According to controls, the discretisation of the power value needed can be foreseen according to the definition of "quantisation of the states" considering as relevant data time, speed, battery power, battery voltage, traction/resistant gear, rpm, ICE (Internal Combustion Engine) etc. By a proper procedure, during which transit time must be considered, the data in the established level must be continually verified. It will also be fixed, as a bandwidth, for the levels mentioned. At last, a definition (already introduced from Inter-university Centre of Transport Research) of the "Hybridization level" will be formulated to describe the large range of existing products. The proposed activities are particularly important in all of the state-of-the-art electric propulsion system research and development sectors, like planning and dimensioning of electric, hybrid multi-traction and multiple energy source vehicles (diesel engine, battery, fuel cell, supercapacitors), validation of energy management algorithms and operating urban and suburban lines with innovative vehicles.

Keywords: traffic and transportation, environmental management, energy resources, air quality.

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1 Introduction

In the LEV (Low Emission Vehicle) field, the hybrid solution has been moderately successful in Italy. These vehicles, besides the usual diesel bus, are equipped with electric and electronic devices, like an electric motor, a generator, a set of batteries and static power converters.

The common configuration in public transport vehicles is the series-hybrid one that uses an electric motor for the propulsion. The energy is supplied by a set of batteries kept charged by a generator driven by an internal combustion engine, which runs at constant (or almost constant) regime in the optimal working point: this solution causes a reduction in pollution and, theoretically, the noise of the vehicle, besides a better energy efficiency. This allows the size of the diesel motor that have to correspond to the medium power required by the vehicle to be defined; contrary to traditional vehicles where this motor is used directly for the propulsion and therefore needs to be bigger in size.

Based on several diffused dates, related to pollution and consumption, it is seen that in the series solution the pollution levels are very much reduced, and so the hybrid vehicle can be considered an "ecological" one. Moreover, for lines with good routes, it is possible to turn-off the generator and to run in "all electric" mode: in fact hybrid vehicles are able to operate whether in LEO (Low Emission Operating) conditions or in ZEO (Zero Emission Operating) conditions. It is important to highlight that some vehicles on the market use alternative fuels like methane or GPL for the internal combustion engine.

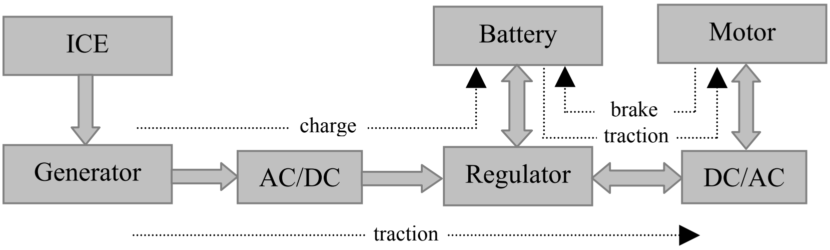

Figure 1: Series-Hybrid bus: main scheme and energy flow.

The first evolution of hybrid vehicles has shown the diversification of models in the market, allowing us to further understand their role in the public transport systems. After all, hybrid vehicles can be considered as an intermediate solution between the battery-propulsion and the trolleybus systems.

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Table 1: Hybrid bus diffusion in Italy at 2003.

Towns	Number of vehicles
Aosta	1
Bologna	22
Brescia	2
Brindisi	2
Campobasso	3
Chieti	4
Civitavecchia	3
Como	2
Ferrara	18
Genova	18
Latina	12
Lucca	3
Mantova	3
Napoli	22
Padova	2
Palermo	23
Parma	8
Pescara	5
Pisa	1
Prato	2
Reggio di Calabria	3
Reggio nell'Emilia	12
Roma	12
Rimini	4
Savona	3
Terni	4
Trento	5
Vercelli	3
Verona	8
Vicenza	1

2 “Hybridization level” definition

Obviously, in a hybrid vehicle, the fixed-point regime of the internal combustion engine has to be optimised for the medium power requirement of the average daily journey, apart from the single running time: different traffic conditions occur during the day.

If the medium power requirement for the line is lower than the medium power supplied by the generator, it is necessary to turn off the internal combustion engine for some periods. This option is particularly interesting when the vehicle crosses cities or pedestrian areas in “all electric” mode. The current trend is to perform this operation by an electronic control system that is able to evaluate the real state of charge of the batteries.

Vice versa, when the medium power requirement mission is higher then the power supplied by the generator, the state of charge progressively decays and it is necessary to make some recharge cycles as well as of the usual battery-pack equalization operations at the depot.

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Figure 2: Hybrid bus 12 meter length in Genoa.

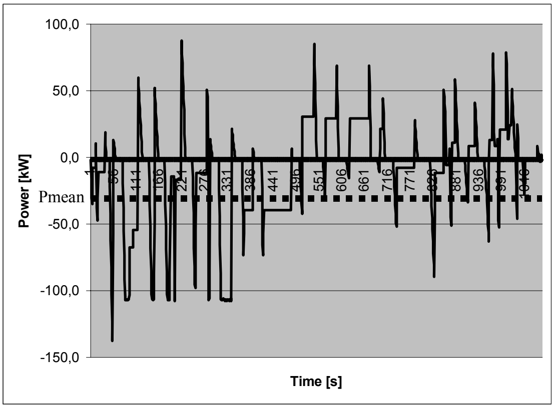

Figure 3: Power profile required during the service and mean value.

Another application of electric engines consists of the diesel-electric solution. The main difference in respect of the hybrid vehicles is that the generator, that is bigger, has a fluctuating regime to follow the load and it supplies energy for the traction directly. In this case it is more correct to refer to “electric transmission” instead of electric propulsion; for diesel-electric buses, the pollution and the consumption are comparable to that of traditional thermic vehicles; the overall pollution emissions are reduced because the energy chain is rationalized and the diesel engine has only to supply the power needed to maintain the set conditions. Conversely, with the traditional transmission the regime is induced by the vehicle speed and by the set gear ratio; this solution is particularly suitable for suburban services, where frequent acceleration and braking are not required.

Moreover, the diesel-electric vehicles gives valid technical solutions to the engineering problems of new generation products, because of the improved features introduced by electric transmission, like, for example, the motor-wheels, that allow the design of very low floors.

Between diesel-electric solutions and those that use only battery packs (“pure” electric traction), are actually performable several intermediate hybrid solutions: a very important concept, introduced by the authors during the meetings of “Electric Vehicles Club” of ASSTRA (Italian association of public transport companies), is the “*Hybridization Level*”, that allows the correct ratio between the traction batteries capacity and the power supplied by the generator to be defined.

A definition of Hybridization Level could be analytically formulated as:

$$i = \frac{2}{\pi} a \tan\left(\frac{P_{bn\,\mathrm{om}}}{P_{ICE}}\right)$$

where P_{ice} is the working power of the internal combustion engine, P_{bnom} is the theoretical nominal value of the battery pack power computable through nominal motor and electronics device power and the battery characteristic discharge curve. In an alternative way, the term can be properly replaced by the nominal value of the power, requested from the control system, according to the use modes of some hybrid vehicles that are on the market at this moment.

In the hypothesis of several “working points” for the internal combustion engine, the Hybridization Level can be referred to as the one with the highest power (theoretical minimum).

Figure 4: All electric vehicle in Genoa (left) and diesel-electric one in Graz.

It is important to note that this level is included between 0 and 1: $i=1$ corresponds to an electric vehicle (all electric bus) and $i=0$ corresponds to a diesel one (no batteries).

The Hybridization Level is not strictly correlated with the vehicle autonomy, but it is a theoretical indication of it; actually, the possibility to maintain a vehicle in energetic balance depends on its use, its route profile, by the speeds, by the break time, and by the eventual generator on-off cycles or intermediate recharge cycles during the service.

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In respect to the definition presented, the actual vehicles can be defined, according to the value of “i” as “minimum” hybrids *(i<0,4)*, “classic” hybrids *(0.4<i<0.8)* and “extended range” *(i>0.7)*, as well as the singular cases of *i=0* and *i=1*.

3 A new generation control logic

In order to obtain an innovative control logic, the typical running cycles have been analysed; obviously, the energy requirements are variable according to the running conditions:

- traffic conditions
- road inclines
- load of passengers
- time tables

Some of these parameters are strongly time-dependent and so it is necessary to preview several “working points” for the internal combustion engine and also an automatic and auto-adaptive procedure to skip among these states.

In the following figure the required functions of the control logic are shown.

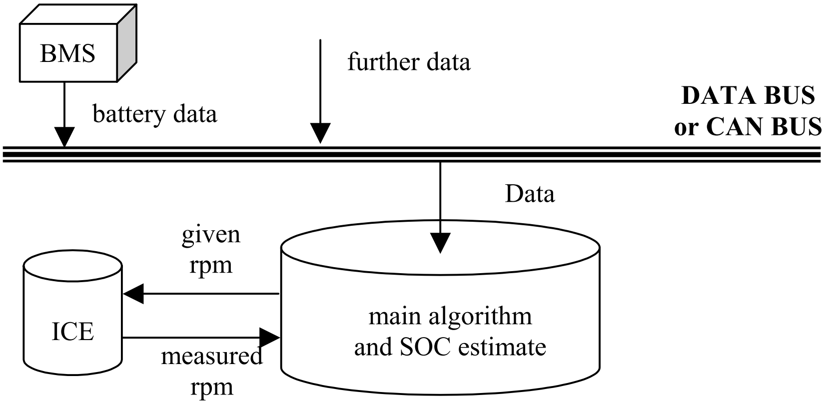

Figure 5: Main scheme of supervision system.

It is possible to observe that the management algorithm acquires the data from an on-board net (eventually CAN Bus), elaborates these data and imposes the proper working state.

In the initial analysis the set of quantities necessary to define the working states are:

- time
- speed

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- battery current
- battery voltage
- traction-braking torque
- rpm of the internal combustion engine
- state ON/OFF of the internal combustion engine
- power of the on-board battery recharger
- SOC (State Of Charge)

Since the objective of the regulation algorithms is to maintain a good state of charge of the traction batteries, it could work in short time on electric data (voltages and currents), while in the middle-long period on the SOC.

Actually, the new generations of traction battery packs are equipped with BMS (Battery Management System) units and thus they give directly the SOC measure. Alternatively it is possible to refer to the battery voltage and current to estimate this value.

As shown in Figure 5, the motor rpm number is the control variable and it is continuously measured to acquire the state of the system. Another main parameter is the state OFF of the internal combustion engine, that can be obtained indirectly but with absolute precision. Theoretically, but with interesting practice consequences, the rpm and so the power control are at closed ring.

A first step through the study of an advanced algorithm for the energetic management of hybrid vehicles can preview, besides the OFF state of the motor, several working states for the internal combustion engine, in growing number, until to evaluate the system response to a continuous working range that is quantised in several points in a [P_{min}, P_{max}] interval corresponding to a [rpm_{min}, rpm_{max}] range.

The related *quantisation of the states* is represented in the following figure, corresponding to an elementary hypothesis based on only two ON states. Moreover, a band-gap will be defined for the considered states.

The working states quantisation is due to the necessity to control the system in closed ring through the knowledge of the system response corresponding to the different working states: in this mode the control is represented by a simple finite state machine.

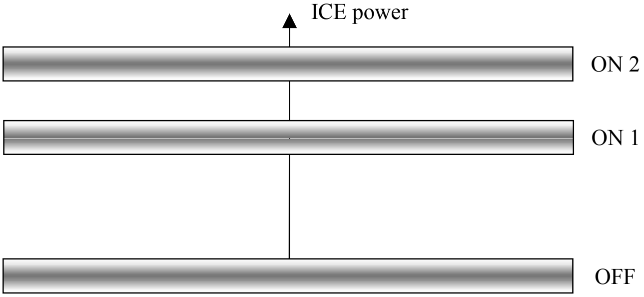

Figure 6: Working states representation (quantisation of the states).

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4 Carrying out logics description

After defining the number and the position of the different working levels of the internal combustion engine (ON states), to make the transitions among these power levels the same algorithm has to supervise the change of state operations. In the initial analysis the transitions between not-adjacent states are not allowed.

According to the minimum pollution and consumption criteria, the supervisor has to perform increasing and descent slopes characterised by a temporal gradient carefully defined. For example, a first, but good, approach could be to consider an increase of 10 kW per second. In the descent slopes, the pollution and consumption problems are negligible and so it is possible to set higher gradients to improve the temporal response of the system.

The turn off procedures can occur for any ON state, according to the normal use for thermic engines; in this case the management algorithm will send the appropriate order; conversely, the starting procedures will be performed by the request from the algorithm and the transition will occur through the lower ON state. In order to perform the proper decisions for the transition between the states, the SOC, defined as a percentage, will be used in assigning values as shown in the following figure.

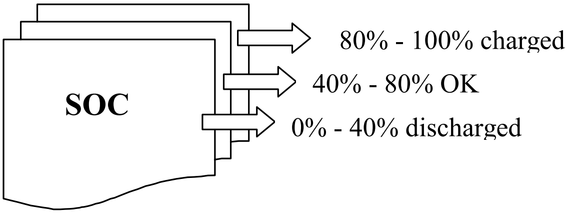

Figure 7: Example of SOC representation.

These illustrative values will have to be parameterised in a configuration file; after, the regulation could be improved in function of the estimate SOC for several levels. The SOC value will be performed according to a mathematic algorithm elaborated and tested on site previously, with very good results.

By the internal clock of the on board microcomputer it is possible to perform the following operations:

- with hour and date, during the starting of the service, to reset the parameters that are dependent on drift or assessable only for their initial state. In the initial analysis it will estimate the starting SOC;
- through the internal clock, to activate all the counters used for the regulation (averages, persistence in the states, hysteresis).

The vehicle speed, measured by (for example) the electric motor rpm, allows the stop conditions to be evaluted. The traction-braking torque give indications about the actual use of the vehicle and it represents an indirect measure of the

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motion resistance. Generally, it gives a measure of the traction and braking operations and, qualitatively, by a simple temporal average and its correlation with the other available physical parameters, recognises the slopes.

As introduced, the ON/OFF state acquirement of the internal combustion engine is important to verify in closed ring a characteristic state of the system (state OFF). By a proper procedure, in which the transition times are considered, the real state has to be verified.

The transitions among the states can also be performed by "*assigning*", according to the "*hysteresis times"* (initially defined or parameterised):

- in the decisional block that performs the states transition, the procedure to evaluate the state has to be improved. If the acquired state is different from the required state, the transition is ordered;
- in the decisional block there is also a control for the ON/OFF transitions induced by the driver; these choices allow:
    - to subordinate the action to the control system
    - to respect the hysteresis times and all the other general rules.

That strategy allows the separation the requirements from the decisions and to always perform the control state verification.

5 Conclusions

After an analysis of the main features of the hybrid bus, an interesting definition of the "Hybridisation Level" has been proposed to better comprehend the evolution of hybrid vehicles involved, given the diversification of the models in the market and their role in the public transport system.

In order to upgrade and refurbish the actual vehicle fleets and to project a new hybrid vehicle generation, it is possible to define a new energetic supervisor. This device is based on a discrete number of working points for the internal combustion engine. In particular, the "Quantisation of the states" definition has been introduced.

Among the acquired parameters, the main one is the SOC (State Of Charge) of the batteries traction, that has to be correctly estimated. This method and definition are relevant to develop energy management algorithms for electric propulsion systems in the field of hybrid multi-traction and multiple energy source vehicles.

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