Method to find the hybridization rate for a parallel hybrid electrical vehicle

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Abstract :

This paper deals with the evaluation of the hybridization rate of a parallel hybrid electrical vehicle (HEV). We propose a control law of hybrid mode which is not dependent of any driving cycles. The veracity of this control law has been evaluated on normalized driving cycle. From results a sizing of the hybrid structure is proposed. The simulations are based on experimental parameters and fuel consumption map.

Introduction

This paper deals with the evaluation of the hybridization rate of a parallel hybrid electrical vehicle (HEV). One of the main difficulty in the design of an HEV architecture consists in finding the optimal percentage of electrical power in relation to the internal combustion engine (ICE) one in order to minimize the fuel consumption under the constraint of an autonomous recharge of the batteries. The difficulty comes from the indetermination of the control laws in hybrid mode : in fact two engines provide the mechanical torque at the wheel; in order to control the speed of the vehicle, it is necessary to know the mechanical torque we want to apply *T_ref*. The estimation of electrical and ICE reference torques from *T_ref* is impossible due the parallel architecture. The inversion of relation described figure 1.a leads to an infinity of solutions as regards T_{ICE_ref} and T_{E_ref}. Therefore it is necessary to elaborate a strategy in hybrid mode in order to overcome this indetermination.

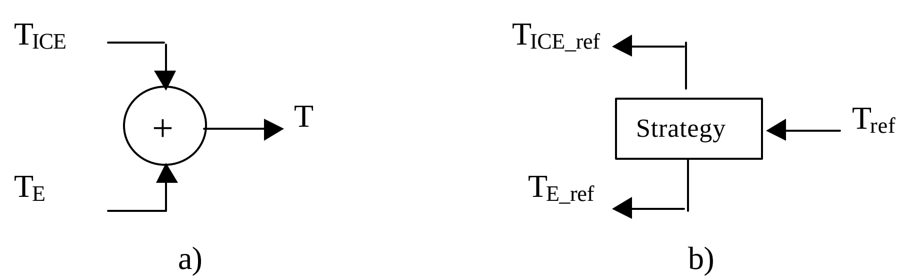

Figure 1
Parallel structure leading to a non unique control law

The authors dealing with the elaboration of a strategy use 'classical' non linear optimization methods [1]. The optimization is calculated on a driving cycle, under the assumption that the chosen driving cycle represents statistically the driving cycles of most drivers. The drawback of this method is the closed horizon optimization, that is to say we suppose the driving cycle is known. However, the diversity of real driving cycles is infinite. Consequently, the optimizations done on closed horizon are not quite valid.

We propose in this paper to determine a control law which is **independent of any driving cycle**. This one is just based on the idea of spending electrical energy which could be recovered during deceleration phases. So in a first part we describe this law and explain how it is possible to predict the electrical energy which could be recovered during deceleration phases.

The design of the architecture is consequently linked with the control laws of the different engines and their use. So, the second part is devoted to the exploitation of the results given by the previous control in order to size the hybrid architecture. Finally, simulation results on normalized driving cycle are showed to prove the veracity of our assumptions.

Control laws for the electrical machine

The parallel hybrid structure offers the opportunity to combine electrical motorization and ICE [2]. Consequently three cases are possible :

– pure ICE mode
– pure electrical mode
– hybrid mode

We are developing the strategies in the different cases and especially in hybrid mode

Pure ICE mode

During the pure ICE mode, the motion of the vehicle is only ensured by the ICE. This control strategy is the simplest one to perform : In fact, during the traction the electrical torque is null and the global torque is equivalent to the ICE torque.

$$\begin{aligned} T_{E\_ref} &= 0 \\ T_{ICE\_ref} &= T_{ref} \end{aligned} \tag{1}$$

In the case when the electrical machine must be acted as a generator, the reference ICE torque must be increased so that :

$$\begin{aligned} T_{E\_ref} &= -T_{gen} \\ T_{ICE\_ref} &= T_{ref} + T_{gen} \end{aligned} \tag{2}$$

where T_{gen} is the generator torque.

Pure electrical mode

During the pure electrical mode, the motion of the vehicle is only ensured by the electrical machine. During the traction, the ICE torque is null and the global torque is equivalent to the electrical torque so that.

$$\begin{aligned} T_{E\_ref} &= T_{ref} \\ T_{ICE\_ref} &= 0 \end{aligned} \tag{3}$$

In this mode, if the ICE is stopped, it can be judicious to declutch the ICE in order to avoid to provide a supplementary torque to compensate the compressions of the ICE.

Hybrid mode

We are going to study in this paragraph a strategy to control both the ICE and the electrical machine. Two cases are possible :

– either a part of ICE torque is replaced by an electrical torque in order to reduce the fuel consumption ; the electrical energy must be recovered during breaking phases : we call it ‘ECONOMIC’ mode

– or we increase temporarily the power of the vehicle which can be useful when the power of ICE is not sufficient : we call it ‘BOOSTER’ mode.

In this paper we will only consider the economic mode because our main objective is to reduce fuel consumption. The booster mode does not correspond to this objective.

The objective of this mode consists of finding an optimal law which allows to reduce the fuel consumption for any elementary speed cycle (acceleration, steady state, deceleration) to the minimum.

Let us consider the following assumptions :

- we suppose an homogeneous behavior of the driver
- we suppose the road is flat (no climbing resistive force)
- we do not consider losses in the electrical machine and in mechanisms
- we do not consider electrical energy management during this elementary cycle
- we consider only positive velocities
- we suppose that the electrical machine ensures the entire breaking force

Let us consider the motion equation where T_{WHEEL} is the torque at the wheel, J_{equ} the equivalent inertia, T_0 friction torque, F_{equ} the aerodynamic force [3]. All these values are defined at the wheel.

$$T_{WHEEL} = J_{equ} \dot{W}_{WHEEL} + T_0 + F_{equ} W_{WHEEL}^2 \tag{4}$$

When the velocity is positive and the acceleration is negative, the torque at the wheel tends to become negative if the deceleration becomes important, that is to say :

$$\left| J_{equ} \dot{W}_{WHEEL} \right| > T_0 + F_{equ} W_{WHEEL}^2 \tag{5}$$

Consequently, when the load torque becomes negative, this one can be used as mechanical energy source convertible into electrical energy via the electrical machine. It is necessary to evaluate the part of inertia force which can be recovered.

So, we propose to calculate the ratio of forces at the wheel during the deceleration in relation to the ones during the acceleration. As regards the homogeneous behavior assumption, we consider acceleration and deceleration equal in absolute value; consequently the ratio h gives us the quantity of mechanical energy which can be recovered and converted into electrical one.

$$h = \left| \frac{-J_{equ} \left| \dot{W}_{WHEEL} \right| + T_0 + F_{equ} W_{WHEEL}^2}{J_{equ} \left| \dot{W}_{WHEEL} \right| + T_0 + F_{equ} W_{WHEEL}^2} \right| \tag{6}$$

We have computed several values of h (figure 2) for different working points. The figure 2 shows only the positive ratio h that is to say working points able to provide electrical energy.

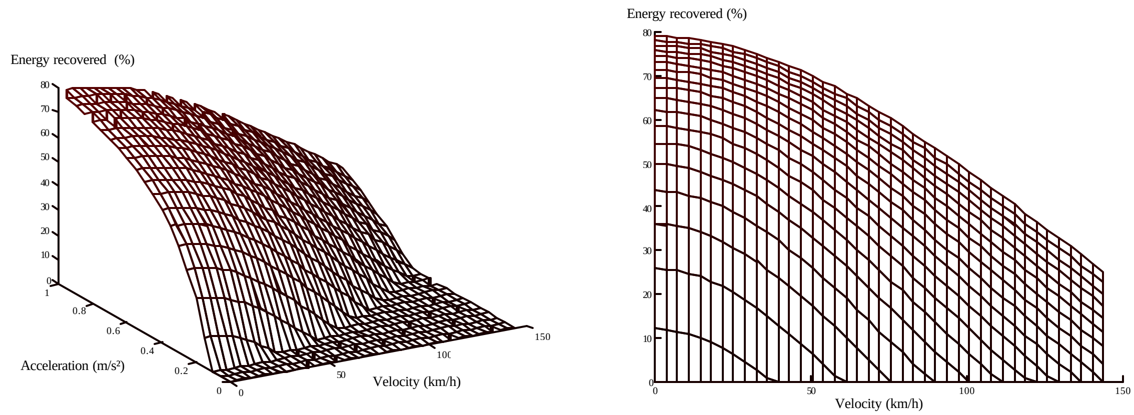

Figure 2
Surface of the positive ratio in the working space

This surface reinforces our main assumption which is based on the use, during acceleration phases, of the electrical energy which could be recovered during decelerating phases. We notice that the value of the ratio is stronger in the working points where the acceleration is the strongest, and null in the steady states. The ECONOMIC mode is only interesting during acceleration phases and all the more important that in these phases the ICE fuel consumption increases.

Consequently, if we assume a driving homogeneous behavior, it is possible to evaluate during the acceleration phases what the energy stored in the inertia is, and to know the quantity of electrical energy which is possible to recover. At each time k, we have to calculate the ratio h for the working point $(W(k),\dot{W}(k))$.

In order to replace a maximum of ICE torque by an electrical torque, with the constraint to recover at the end of each elementary cycle all the electrical energy spent, we applied **during the acceleration phase the following control laws**

$$\begin{aligned} T_{E\_ref} &= hT_{ref} \\ T_{ICE\_ref} &= (1-h)T_{ref} \end{aligned} \qquad (7)$$

with

$$h = \left| \frac{-J_{equ}\left|\dot{W}_{WHEEL}(k)\right| + T_0 + F_{equ}W_{WHEEL}^2(k)}{J_{equ}\left|\dot{W}_{WHEEL}(k)\right| + T_0 + F_{equ}W_{WHEEL}^2(k)} \right| \text{ if } J_{equ}\left|\dot{W}_{WHEEL}(k)\right| > T_0 + F_{equ}W_{WHEEL}^2(k) \qquad (8)$$

and

$$h = 0 \text{ if } J_{equ}\left|\dot{W}_{WHEEL}(k)\right| \le T_0 + F_{equ}W_{WHEEL}^2(k) \qquad (9)$$

Sizing the electrical machine

Extreme elementary cycle.

In this paragraph, we will describe how to define the electrical machines features using the hybrid control law. Our study is referring to the normalized EUROPE cycles. We notice that the most important acceleration is about 1.04 m/s^2. We decide to perform the worst elementary cycle we could meet in reality. So we impose a maximal acceleration until we reach the maximum velocity and to apply a maximum deceleration until we stop the vehicle. This simulation will allow us to define the maximal torque, the maximal power and the maximal energy savings using hybrid strategy. We take into account the efficiency of the ICE through the fuel consumption map. The weight of the vehicle is 1200Kg. We assume no electrical loss.

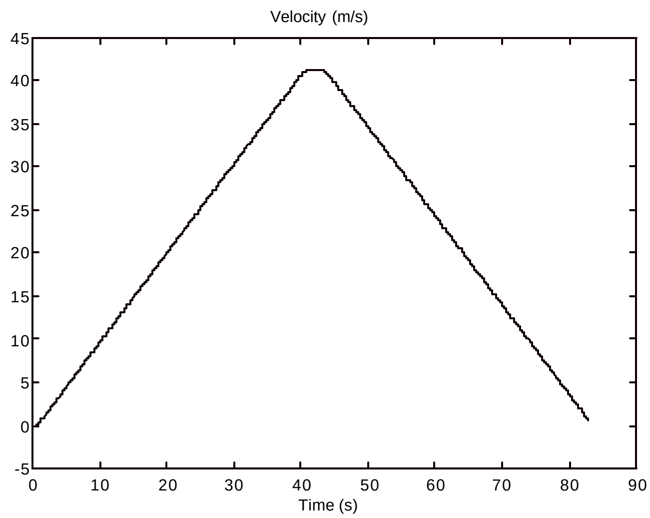

Figure 3
Extreme elementary speed cycle

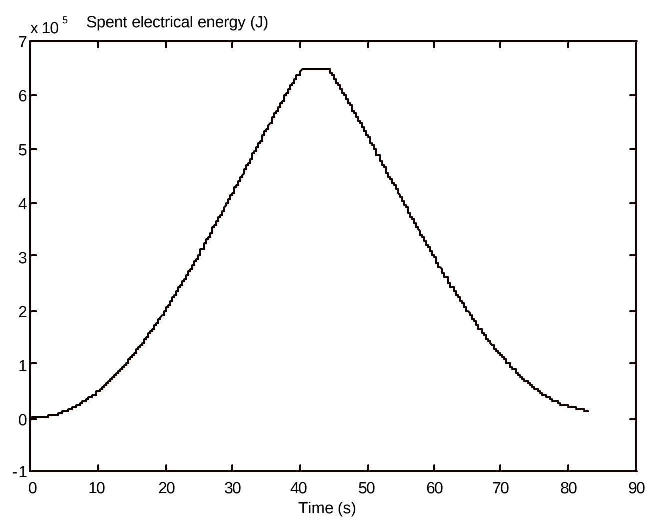

Figure 4
Assessment of electrical energy

Figure 3 shows the extreme elementary cycle. Figure 4 proves the veracity of our control law as regards the autonomous recharge of the batteries and gives information about the required storage of the electrical energy.

For different limitations of the electromechanical torque, the simulation of the extreme elementary driving cycle gives us the percentage of fuel savings (figure 5).

We have simulated several electromechanical torques limitations on the same elementary cycle, and consequently we have verified the existence of an optimal electromechanical torque.

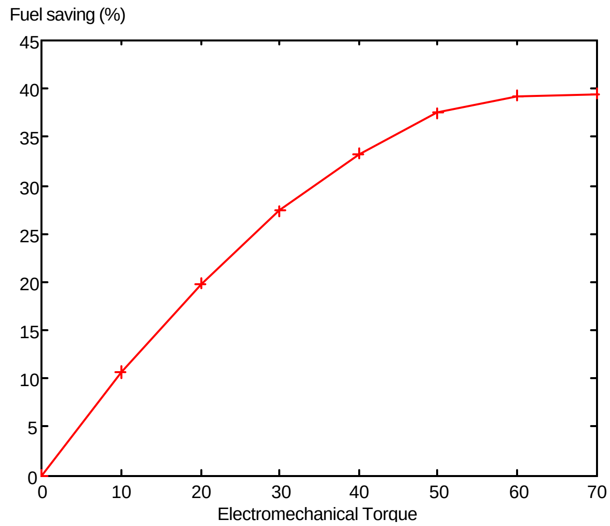

Figure 5
Fuel saving using ECONOMIC mode

- **Sizing of the electrical machine** *:*

We notices on the figure 5, that is not useful to size the maximal electromechanical torque beyond 60N.m (23 kW required electromechanical power) in our application using ECONOMIC mode. Considering a 60 kW ICE, the hybridization rate becomes 38%.

- **Sizing of the electrical energy storage***:*

Figure 4 gives information about electrical energy storage which is necessary for the ECONOMIC mode : this one is equal to 7.10^5 J. This piece of information will allow us to estimate the number and the weight of the batteries. The weight of the batteries must be added to the global mass of the vehicle, and it is necessary to refine the parameters of the system.

Simulations on the EUROPE NF R 11-502 cycle.

Although, our hybrid control law is not dependent of any driving cycle, in order to prove the efficiency of the 'ECONOMIC' mode, we have tested it on the cycle EUROPE NF R 11502 taking the ICE fuel consumption map into account. Figure 6 represents this driving cycle. Any other classical normalized driving cycle could have been used for this test [4].

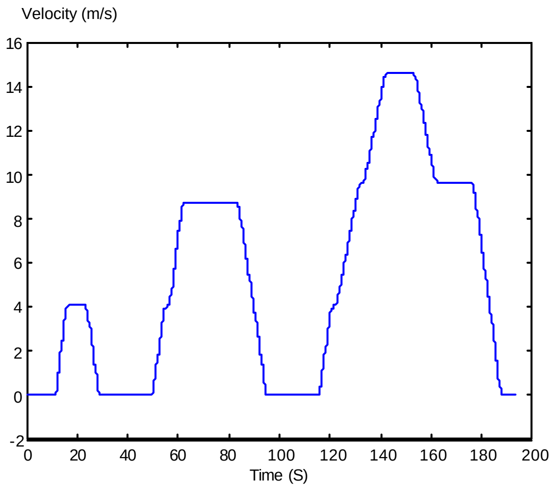

Figure 6
***EUROPE NF R 11-502* Speed cycle**

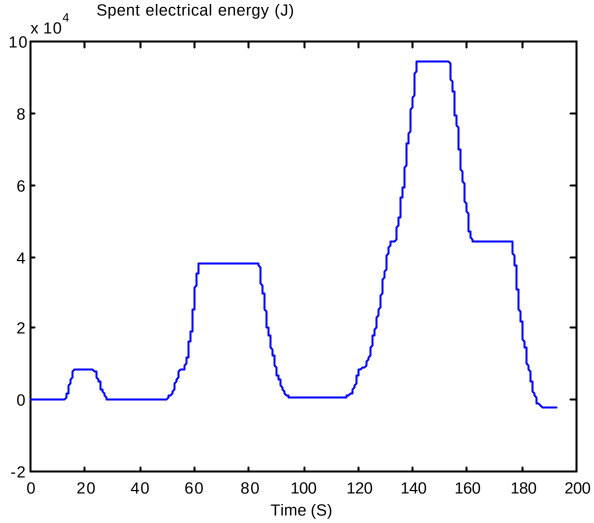

Figure 7
Assessment of electrical energy

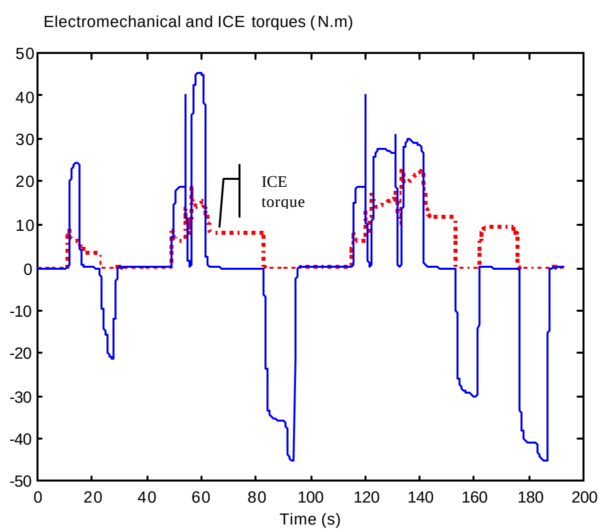

Figure 8
Electromechanical (-) and ICE (...) torques at the shaft

We sketch the fuel accumulated consumption during the cycle with and without hybrid strategies.

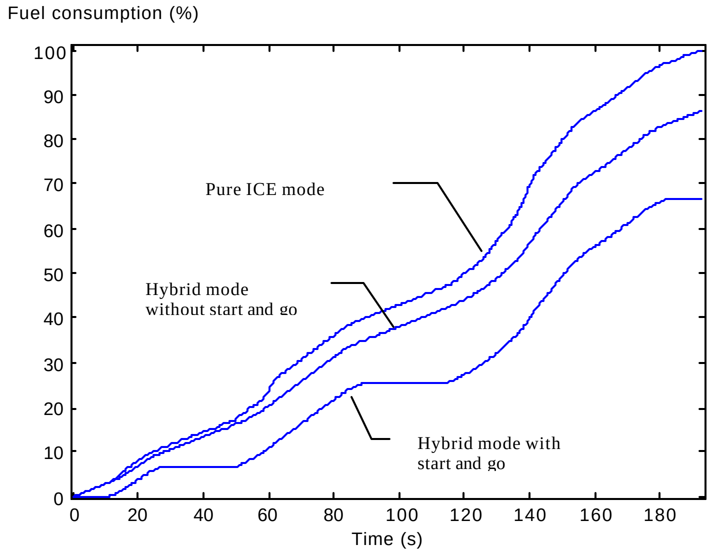

Figure 9
Fuel consumption of different control laws

We can discuss about the validity of the symmetric behavior assumption. This assumption is not really wrong as regards the normalized cycles (figure 6).

Figure 7 proves the veracity of our strategy as regards the electrical energy spent. We can see that the difference of the electrical energy at the end of the cycle in relation to the beginning is very small. This is due to the non symmetric driving behavior. We can imagine to correct the difference in the reality by evaluating correlation between the acceleration and deceleration. Artificial neural networks are well suited for this type of problem [5]. For example, an artificial neural networks could be employed to this estimation and after learning phases could be used to weight the ratio η in relation to imposed acceleration. Many data are necessary to determine a correlation between the accelerations and the decelerations.

We notice a fuel saving of about 14%, which is relatively far from the expected 40% of the test on the extreme elementary speed cycle used to size the electrical machine. This deviation is due in fact that, during the NF R 11-502 transients, the ICE torques breed fuel consumptions near by steady states fuel consumptions. So, the substitution of a part of global torque using the electrical machine does not allow a noticeable decreasing of the fuel consumption in the working areas of low gradient consumptions. Nevertheless, if the start and go option is selected, the fuel saving can reach 33%. This option can be performed using a starter alternator. A prototype of such electrical machine has been realized in collaboration with our laboratory [6]. This prototype is directly mounted on the ICE shaft; due to the position of the electrical machine to the clutch, the pure electrical mode is not possible. However, this structure is also an hybrid architecture which allows the hybrid and pure ICE modes. Consequently, our hybrid control law is still valid for such a structure.

Conclusion

In this paper, we have proposed a control law for the hybrid mode of a parallel hybrid electrical vehicle which is **independent of any driving cycle**. We have compared energies during acceleration and deceleration phases. Using the motion equation we are able to predict from acceleration phase the behavior of the driver during the deceleration phase; consequently we predict the electrical energy which could be recovered, and this leads us to spend only this electrical energy during the acceleration phase.

Using this control law of the hybrid mode, **we have shown how to size the electrical machine and electrical energy storage**, from an extreme elementary cycle. However, the sizing is dependent of the maximal expected performances. Consequently, it is necessary to evaluate the use of hybrid vehicles and the expected performances.

An evaluation of our strategy has been simulated on the normalized NF R 11-502 driving cycle. Although the fuel savings are still small (respectively 14% and 33% without and with start and go option), results prove the veracity of this strategy and the validity of our assumptions.

The utilization of the electrical machine in parallel with ICE during transients allows to reduce the power of the ICE. This evident remark leads to two ways of research :

- either we try to optimize the electrical equipment in relation to an existing ICE
- or we try to optimize both the electrical equipment and ICE

If it is possible to modify the features of the ICE in relation to the sizes of the electrical machine, it is necessary to take into account the weight decreasing and the fuel consumption of the new ICE. Although this second way is not really intended by ICE builders, it should be the most optimal of these two ways.

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