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Optimal control of a small hybrid car

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ABSTRACT

The stringent fuel consumption and pollutants reduction standards enforce manufacturers and carmakers to have a closer look on new powertrain architectures for passenger cars. In that context, studies on hybrid vehicles appear today in a substantial scale. The association of a high efficiency electrical motor with an internal combustion engine needs specific control laws in order to optimize the energy transfer management. This paper presents a new control strategy developed by SiemensVDO Automotive and the LEEI laboratory on an small and mild hybrid vehicles. A supervisor with the full control of the drive train (clutch, gearshifts, thermal IC engine torque and electrical motor torque) allows to improve fuel consumption and to maintain an admissible battery state of charge. It also provides the optimal gear ratio that can be applied according to acceleration constrains. This includes the concept of driveability in the criterion that is often in contradiction with energy savings.

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Key words : Optimization, hybrid vehicles, control algorithm, criterion function

1. INTRODUCTION

The stringent fuel consumption and pollutants restriction standards impose car manufacturers to enhance the energy management of the vehicle. Two ways are being investigated. Standard solutions are based on a more precise control of the fuel combustion in the cylinders. To do so, the engine bloc has to contain more and more electronically controlled devices such as air throttle, egr valve, and injection. Intake and exhaust valves are also controlled on the most recent applications. But this high technology reaches its limits, with the risk of less profitability due to the development costs.

A second development step is necessary. Car manufacturers are looking for new drive train architecture. A lot of studies on hybrid vehicles appear. Hybrid vehicles associate the internal combustion engine with a non-pollutant high-efficiency electrical motor. Specific control laws allow to save fuel and thus reduce pollutants emissions, with no degradation of the car driveability.

Hybrid vehicles offer an additional degree of freedom to fulfill the driver's request. A supervisor-like controller can be developed thank to the possible management of two motorizations. Then the supervisor is tuned in order to compute the optimal vehicle working point in term of fuel consumption and driveability. This paper presents a way to manage the drive train. It is based on the optimization of a criterion that integrates both consumption and driveability aspects.

2. SMALL HYBRID CAR

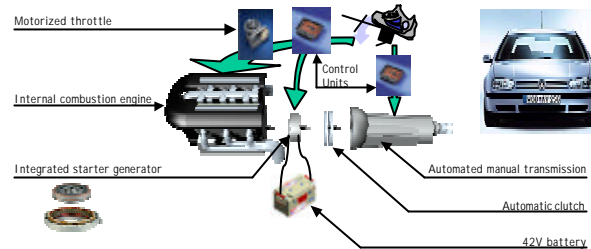


figure 1 : drivetrain architecture

The drive train architecture used in the study is shown on figure 1. This is a small hybrid vehicle : both engine are linked together and the electrical motor cannot run without the thermal engine. The integrated starter-generator has a nominal power of 6kW and is mainly used to provide an additional torque to the engine (which has a maximum power of 70kW) or to charge the battery. Nevertheless, the algorithm developed in this article is independent from that power ratio and can be applied on every system that presents a similar architecture.

The Starter-Generator is developed by Siemens VDO Automotive. It is supplied by an AC/DC converter linked to a 42V battery. The motor is directly mounted on the engine shaft. It is sized so that it can start the engine and provide additional torque in *motor* mode. In *generator* mode, it is able to charge the battery.

The thermal engine is a gasoline internal combustion engine with an electronic intake throttle control. The calculator also regulates the fuel flow so that it allows the software to have a full control of the torque produced by the engine.

The vehicle also benefits of an automated manual transmission. It is composed of a motorized clutch and a 5 speed gear box. The system is driven by sequential commands to realize upshifts or downshifts. The transmission control unit can also automatically manage the gearshift.

The global powertrain is thus controlled by the supervisor, to manage the torque repartition between the two motorizations and decide of the optimal gear to be engaged, to best fit the desired vehicle's behavior.

3. OPTIMIZATION DOMAIN

The first step of development of an optimization is to analyze the possibilities of the system. The main constraints are the consequence of physical limitations on the different parts of the drive train. The torque produced by the engine and the starter-generator are naturally limited regarding to the technology used. The battery type also imposes limitations on the battery state of charge and on the reachable voltages. The gear box's architecture makes the achievable engine speed close related to the vehicle speed.

The first constrain to take into account is the driver's request. This request is interpreted in terms of power. This value is quite easy to use because the power from the propulsive bloc is equal to the power request at wheels plus the drive train losses. The drive train losses can be approximated in order to consider them independent from the gear-ratio. Then the power request at the propulsive bloc is considered independent from the engine speed. The system has to respect the equation (1) where P_{ISG} is the mechanical power of the starter-generator (ISG stands for Integrated Starter-Generator), P_{ICE} is the mechanical power of the engine (ICE stands for Internal Combustion Engine) and P_{REQ} is the power request at the propulsive bloc (REQ stands for request).

$$P_{ISG} + P_{ICE} = P_{REQ} \quad (1)$$

The constraints that the optimization has to fit can be expressed in the 5-equations system (S). TQ represents a torque, ω is a rotation speed and SOC is the state of charge of the battery.

$$\left\{ \begin{array}{l} (TQ_{ISG} + TQ_{ICE}) \cdot \omega_{ICE} = P_{REQ} \end{array} \right. \quad (1')$$

$$\left\{ \begin{array}{l} TQ_{ISG}^{MIN}(\omega_{ICE}) \leq TQ_{ISG} \leq TQ_{ISG}^{MAX}(\omega_{ICE}) \end{array} \right. \quad (2)$$

$$\left\{ \begin{array}{l} TQ_{ICE} \in D_{TQ} \end{array} \right. \quad (3)$$

$$\left\{ \begin{array}{l} \omega_{ICE} \in D_{\omega} \end{array} \right. \quad (4)$$

$$\left\{ \begin{array}{l} SOC_{MIN} \leq SOC \leq SOC_{MAX} \end{array} \right. \quad (5)$$

The starter-generator torque is limited to a minimal negative value TQ_{ISG}^{MIN} . It is the minimum

effort that the starter-generator can apply to the engine shaft in generator mode. TQ_{ISG}^{MAX} is the maximum torque in motor mode. Those limitations are computed in order to take into account the voltage variations of the battery that result from the current generated or consumed by the starter-generator. The battery voltage has to remain inside a certain set of acceptable values.

D_{TQ} is the domain of admissible engine torque. It is shown on figure 2. That domain is made of two parts. The first one is the positive domain limited by a maximum curve, the second part is a negative curve representing the engine losses when no fuel is injected into the cylinders (it is supposed that no negative torque different from the engine internal losses can be achieved). This means that the engine can not continuously vary from a positive torque to a negative one.

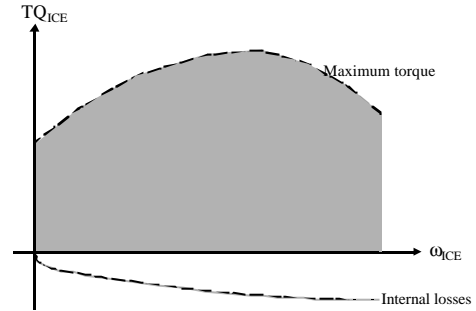


figure 2 : Admissible engine torque representation

The D_{ω} domain depends on the vehicle speed and the different drive train ratios ρ_i (we note D_{ρ} the set of drive train ratios). This is a discrete domain that contains as many values as gearbox ratios. To be acceptable, those values have to be within ω_{MAX} (the maximum speed that engine can support) and ω_{MIN} (the minimum engine speed that ensures a correct combustion of the fuel). The equation (6) gives a mathematical representation of this domain.

$$D_{\omega} = \left\{ \omega_i = \frac{V}{r_i} \in [\omega_{MIN} \quad \omega_{MAX}] / r_i \in D_r \right\} \quad (6)$$

The battery state of charge has to be maintained between SOC_{max} , the maximum energy that can be stored in the battery, and SOC_{min} . This minimal value prevents the battery

from deep discharge that would damage it and shorten its life expectancy.

There are three variables to set the vehicle working point :

- the engine torque
- the ISG torque
- the engine speed that is defined from the gear ratio

The constrain (1') clearly shows that these 3 variables are linked together. So the optimization domain has a maximum degree of freedom of 2. Finally the optimization domain can be represented in the engine torque – engine speed domain (see figure 3).

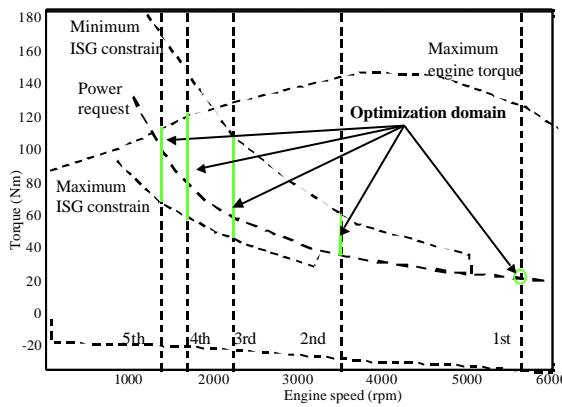


figure 3 : optimization domain

4. TARGET BEHAVIOR

As it is shown on figure 3, there is an infinity of possible solutions to fulfill the driver request. An expected behavior has to be defined for the vehicle considering the acceleration, the behavior of the car and the efficiency of the drivetrain. Two main aims are described in this paragraph.

4.1. Driveability

The driveability is the capacity of the car to fulfill the driver's acceleration demand. This is mainly ensured by the constrain (1) but it is not enough. But this constrain can lead to undesired behavior. For example, when an acceleration of the vehicle is required, the system could decide of a

downshift in order to fulfill the increased power request. The drivetrain is then open to allow the gear shift and no torque is transmitted to the wheel during a few second.

A power reserve is set in order to avoid this kind of behavior. If the difference between the maximum achievable power at the computed gear ratio and the power request is lower than the power reserve, then the criterion is penalized. Thanks to this, the vehicle will always have some additional acceleration possibilities at the actual gear engaged. The figure 4 shows the different behavior on a system with and without power reserve (PV_AV is the acceleration pedal value).

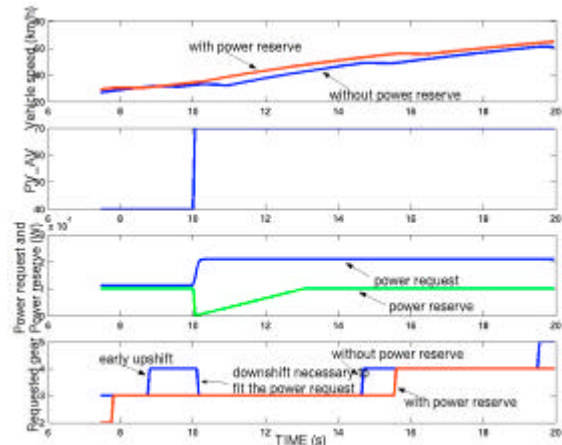


figure 4 : Preventing downshifts on acceleration with a power reserve

4.2. Consumption reduction

The first aim of those algorithm is to reduce the fuel consumption. The optimization 's criterion has then to integrate the power taken from the energy sources (fuel tank and battery). The power consumed can be written as in equation (7).

$$P_{conso} = \frac{P_{eng}}{h_{eng}} + \frac{P_{isg}}{h_{elec}} \quad (7)$$

Considering such a criterion will automatically leads the system to a total discharge of the battery. As the efficiency of the electrical part (battery+AC/DC converter+ISG) is much

higher than the engine efficiency, the use of the ISG in motor mode cost less energy.

The electrical power taken from the battery must be given back using the ISG in generator mode and thus consuming fuel. This future consumption is integrated into the criterion by an estimation of the relative cost of the electrical power. The management of the energy used for the vehicle's propulsion has also to ensure that the battery state of charge is maintained at a correct level. To do so, the relative cost of the electrical power is made dependant on the state of charge. The criterion is then shown in equation (8).

$$Crit = \frac{P_{eng}}{h_{eng}} + a(SOC) \cdot \frac{P_{isg}}{h_{elec}} \quad (8)$$

The relative cost α has to follow some rules:

- 1) it should decrease when the SOC value increase
- 2) its value at the minimum authorized SOC value should be infinity (or at a very high value)
- 3) its value at the maximum authorized SOC value should be zero (or at a low value)

A possible evolution curve of the α coefficient is shown in figure 5. Those rules ensure that the SOC will remain between the minimum and the maximum value.

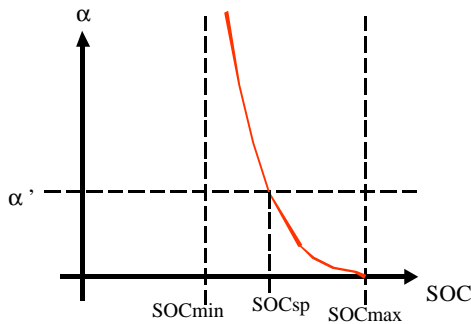


figure 5 : Example of possible evolution of the coefficient α

Thanks to equation (1), the criterion can be rewritten as in equation (9)

$$Crit = \frac{P_{req}}{h_{eng}} + \left(\frac{a(SOC)}{h_{elec}} - \frac{1}{h_{eng}} \right) \cdot P_{isg} \quad (9)$$

If α is lower than $a' = h_{elec}/h_{eng}$, the cost of the electrical energy is considered to be low.

Thus the ISG is used in motor mode, the SOC will decrease and α will increase.

If α is higher than α' , the ISG is used in generator mode, the SOC will increase and α will decrease.

On a stabilized point, the value of α will be equal to α' . So this coefficient will always converge to the ratio of the two efficiencies. It has a slow dynamic, the same as the SOC value. It can be considered as a filtering of the ratio of the efficiencies. Consequently, the value $a(SOC) \cdot \frac{P_{isg}}{h_{elec}}$ represents an estimation of the additional fuel consumption that will be necessary to maintain the battery SOC.

The shape of the α curve can also be used to minimize or limit the battery SOC variation. If we have an estimation α' of the ratio of the efficiency (around the value of 3) then we can tune the curve in order to have it cross α' at a specified SOCsp. The value of the SOC will evolve around SOCsp during the travel.

This evolution of the cost of electrical energy lets a freely use of the ISG to the algorithms but prevents the battery from large state of charge variations.

The figure 6 and 7 show the battery state of charge evolution that can be obtained on the european and japanese cycles with a SOCsp constant value of 70%. The european cycle starts with a cold engine. Consequently the engine efficiency is low. The optimal computed behavior is then to use the ISG in motor mode. The battery is recharged when the engine efficiency is higher.

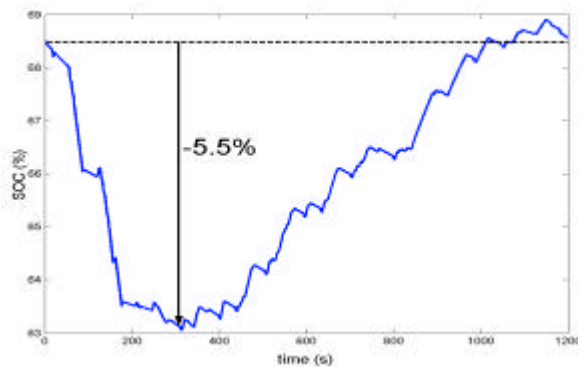


figure 6 : SOC evolution on the european cycle

The japanese cycle starts with a warm engine. The differences of engine efficiency are smaller than in the european cycle ; so the state of charge has a very little variation.

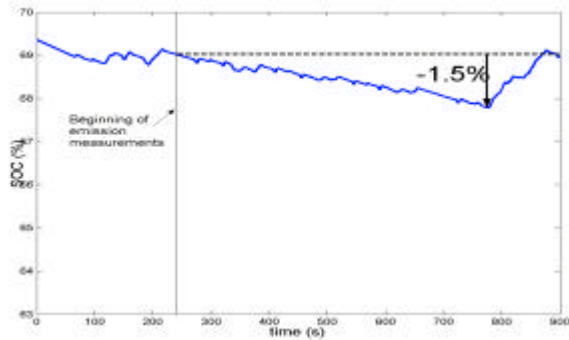


figure 7 : SOC evolution on the japanese cycle

The results of the working point optimization are -13% of fuel consumption on the japanese cycle. The reference is a standard vehicle without ISG nor automated manual transmission.

5. CONCLUSION

The association of several motorizations of the drive train makes necessary the definition of a supervisor to manage both driveability and fuel consumption reduction. This paper shows a method based on an optimization which can ensure these requirements from a well defined criterion.