FUEL CONSUMPTION OPTIMIZATION FOR HYBRID SOLAR VEHICLE

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Abstract: Hybrid electric vehicles (HEVs), having multiple main energy sources, are an attractive alternative to conventional vehicles. The paper presents a study on minimizing the energy consumption in a series hybrid solar vehicle (HSV). First a description of the series HSV is given, after which two control strategies are presented for fuel consumption optimization. The first control strategy is dynamic programming (DP) which is used to obtain a global optimum for fuel consumption. The second control algorithm is Model Predictive Control, implemented using multi-parametric programming, for which the calculations and simulations were performed using the Multi-Parametric Toolbox (MPT). Both strategies are tested through simulations.

Keywords: hybrid solar vehicles (HSV), control strategies, dynamical programming (DP), multi-parametric programming, piecewise affine (PWA) function

1. INTRODUCTION

Hybrid electric vehicles (HEVs), having multiple main energy sources, are an alternative to conventional vehicles. More and more importance is dedicated to research in this field of alternative vehicles. These energy sources are the conventional fuel tank and a battery, delivering both chemical and electrical energy. If a photovoltaic panel is also added, a Hybrid Solar Vehicle (HSV) is obtained. HSVs can be seen as a transition from conventional vehicles to fully electric vehicles. The architecture of HSVs can be different, depending on the requirements imposed. Basic drivetrain structures for HSVs are: series, parallel, series/parallel and complex hybrids. Since the target of the research is optimization of fuel consumption in case of urban drive cycles, a series architecture was chosen for this study, this proving to be optimal in this case. A basic diagram of the series HSV is depicted in Figure 1.

First a brief model of the series HSV is described, after which two control strategies are presented for fuel consumption optimization. The two control strategies are based on two different models of the HSV, the first one being based on static maps and the other on the basic dynamics of the vehicle. The first control strategy is based on dynamic programming (DP), which is actually used to obtain a global optimum for fuel consumption. The reference signal consists of several urban cycles. The result is an input sequence of motor power values. Since DP is not a feasible solution for practical implementation due to its computational time, an alternative control strategy consists in Model Predictive Control (MPC), implemented in the paper using multi-parametric programming. For design and simulation the Multi-Parametric Toolbox (MPT) and other tools are used, the MPT having the advantage of delivering an explicit solution for the control signal. A piecewise affine (PWA) model is associated to the HSV and integrated into a multi-parametric programming problem of the constrained optimization.

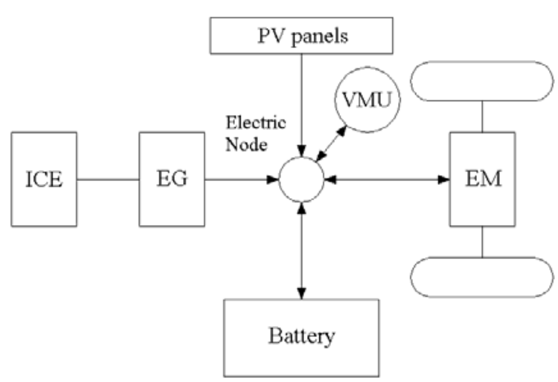

Fig.1. Basic diagram of a series HSV

As solution, the state space is partitioned into polyhedral sets, and the optimal control law for each set is an affine function of the state, this way the global solution is a PWA function of the state. Both strategies are tested through simulations.

2. CONTROL STRETEGIES FOR FUEL CONSUMPTION FOR SERIES HSV

For both control strategies models of the series HSV are required. Since DP realizes a search between different static working points, static maps are used for modelling in case of DP. These static maps are related to the internal combustion engine (ICE), electric generator (EG), photovoltaic panels (PV panels), battery and electric machine (EM).

On the other hand, the use of MPC (implemented with MPT) requires a dynamical mathematical model of the plant. The model of the vehicle contains only the basic system dynamics, consisting of the simple longitudinal dynamics of the vehicle (according to Newton's second law), the simple dynamics of the battery and the dynamical relation between alternator power and fuel consumption related to it. PWA models are built for this purpose, in form of:

$$\begin{aligned} x(k+1) &= A_d x(k) + B_d u(k) + f_d \\ y(k) &= C_d x(k) + D_d u(k) + g_d \end{aligned} \tag{1}$$

The model is structured on more dynamics, and for each dynamic a PWA state-space description is given. The states of the system characterize the vehicle velocity, the battery energy level and fuel amount consumed.

As far as the control is concerned, two strategies are presented and tested through simulation using Matlab/Simulink environment. The first strategy is DP, as mentioned previously, based on the model created using static maps. A global optimal solution for the electric energy management of the car can be achieved with DP. The algorithm creates the so called cost-to-go matrix recursively from the end point to the start point of the chosen drive cycle. It is defined a feasible energy or state of charge (SOC) window for the drive cycle. The upper limit means the maximum available battery energy level or the maximum energy level from which the battery energy could be decreased to the final value during the rest of the drive cycle. The lower limit means the minimum energy level or the minimum energy level from which the battery energy could be increased to the final value during the rest of the drive cycle. The bounds on the SOC are presented in Figure 2.

During optimization, the first step is the discretization of the drive cycle and of the feasible battery energy window. Then the cost-to-go matrix is calculated from the final point to the initial point. This contains fuel optimal paths and the global optimal path is followed starting from the initial point. From the matrix the optimal sequence for battery power and for the total fuel consumption results. The system is finally simulated using this optimal sequence.

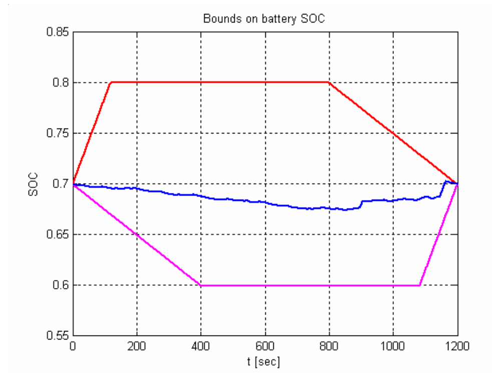

Fig.2. Bounds on battery SOC

The second control strategy applied is MPC implemented using the MPT, here PWA models are used. Optimal control of PWA systems is of interest since these systems can well approximate non-linear systems and they are equivalent to hybrid systems. The MPT toolbox can be used for design of optimal and sub-optimal control laws, either in implicit or in explicit form. By multi-parametric programming, a linear or quadratic optimization problem is solved off-line, resulting in an explicit controller. Even though the multi-parametric approaches rely on off-line computation of a feedback law, the computation can become prohibitive for larger problems. This is mainly due the exponential number of transitions between regions which can occur.

The explicit controller is implemented in the form of PWA control laws:

$$U(k) = F_i^r x(k) + G_i^r \tag{2}$$

where i represents the active dynamics and r represents the active region (the region which contains the given state $x(k)$).

Prior to applying the control law to the plant, the proper control law has to be identified. This is achieved by checking which region of the controller contains the given state. This operation may be extremely difficult in case of very complex controllers, and in this case a complexity reduction (simplification) in controller partitions can be performed.

As simulation example a reference tracking controller is presented for a 6 dynamics vehicle model, using a linear cost function with infinite norm. The controller having 278 regions is depicted in Figure 3.

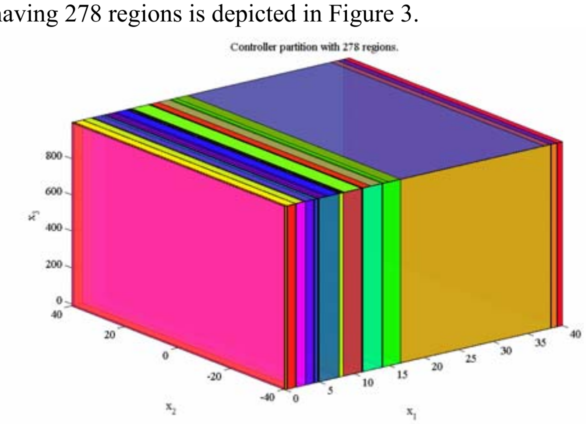

Fig.3. Controller regions

7. CONCLUSION

The paper presents two solutions for fuel consumption optimization for series Hybrid Solar Vehicles (HSVs). HSVs, having multiple main energy sources, are an alternative to conventional vehicles.

Based on a brief description of the models of a series HSV, two control strategies are presented for fuel consumption optimization.

The first control strategy is dynamic programming (DP) which is used to obtain a global optimum for fuel consumption. This is not an on-line solution, since it assumes that the future reference is entirely known. In the paper a DP solution was given, showing that the energy management concept is working for a pre-defined drive-cycle.

The second control algorithm is Model Predictive Control, implemented using multi-parametric programming for which the calculations and simulations were performed using the Multi-Parametric Toolbox (MPT). Multi-parametric programming offers the possibility of obtaining an explicit solution of the control law, this reducing the calculation effort. Of course, the solution is only valid if the problem is not much too complex, and the number of regions does not exceed the calculation possibilities. Simulations were performed for different scenarios (different control tasks having different references, control horizons etc.), obtaining controllers with different complexity (number of regions) in order to see the behaviour of the system signals: output, control signal and states.

Nevertheless, also the active dynamics characterizing each region are depicted, as function of the system behaviour. The simulations reflect that MPT can be used for HSV control due to the theoretical and implementation aspects that characterize it.

The test simulations are performed for both strategies using Matlab/Simulink environment .

Finally, in this phase of the developments it can be stated that the control strategies used for energy management can be very well used. Further and more detailed simulations will be performed, especially using the MPT toolbox, in order to sustain a latter physical implementation on the real system.

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