Hybrid Electrical Vehicles : From Optimisation Toward Real-Time Control Strategies

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■ Growing environmental concerns coupled with concerns about global crude oil supplies stimulate research on new vehicle technologies. Hybrid-Electric Vehicles (HEV) appear to be one of the most promising technologies for reducing fuel consumption and pollutant emissions.
In this paper is assessed the potential of different powertrain architectures for HEV [1], and different control laws are tested. So as to do that, the complete vehicle is modelled in order to simulate driving cycles and evaluate the gain in fuel consumption and pollutant emissions.

■ The different powertrain architectures are modelled in AMESim environment ([2], [3]) : from the mild-hybrid, where the electric motor just assists the engine, to the full-hybrid where the engine can be turned off during a finite time. The size of elements, as the size of the supercapacitors (used instead of classical batteries), are also tested on different driving cycles.
So as to characterize the different powertrain architecture, the energy repartition between the engine and electric motor is optimized with respect to fuel consumption and pollutant reductions. To perform this optimization on a driving cycle, a Dynamic Programming algorithm based on a reduced model is implemented.

■ The reduced model (written in Matlab) consists in considering the following supercapacitors model :

$$\frac{dSoc(t)}{dt} = -\frac{Ne(t)\cdot TME(t)}{U(t)\cdot capacity} \tag{1}$$

in continuous time, which in discrete time becomes :

$$Soc(k+1) = Soc(k) - \frac{Ne(k)\cdot TME(k)}{U(k)\cdot capacity}\Delta t \tag{2}$$

The torque repartition between the electric motor torque (TME) and the engine torque (TMT) is expressed as follow, the expected torque *Torque(k)* being given from the driving cycle :

$$TMT(k) = u(k).Torque(k) \tag{3}$$
$$TME(k) = (1-u(k)).Torque(k) \tag{4}$$

Constraints on command and on maximal and minimal acceptable values of the State of Charge (Soc) of the supercapacitors are imposed :

$$0 \le u_{\min}(k) \le u(k) \le u_{\max}(k) \le 1 \tag{5}$$
$$Soc_{\min} \le Soc(k) \le Soc_{\max} \tag{6}$$

The Dynamic Programming approach ([4], [5]), is used to find the optimal energy repartition. The criterion to be minimised is the total fuel consumption. The optimisation problem is thus :

$$\min_{u(k)} J(u) := \sum_{k=0}^{N-1} L(X(k),u(k),k) + g(X(N),N) \tag{7}$$

u(k) subject to (5) and (6)

where *L(X(k),u(k),k)* is fuel consumption over the time interval [k,k+1], *X(k)* is the State of charge of the supercapacitors at time *k*, *N* is the final time of the driving cycle, and *g* is a function which constrains the final state of charge.

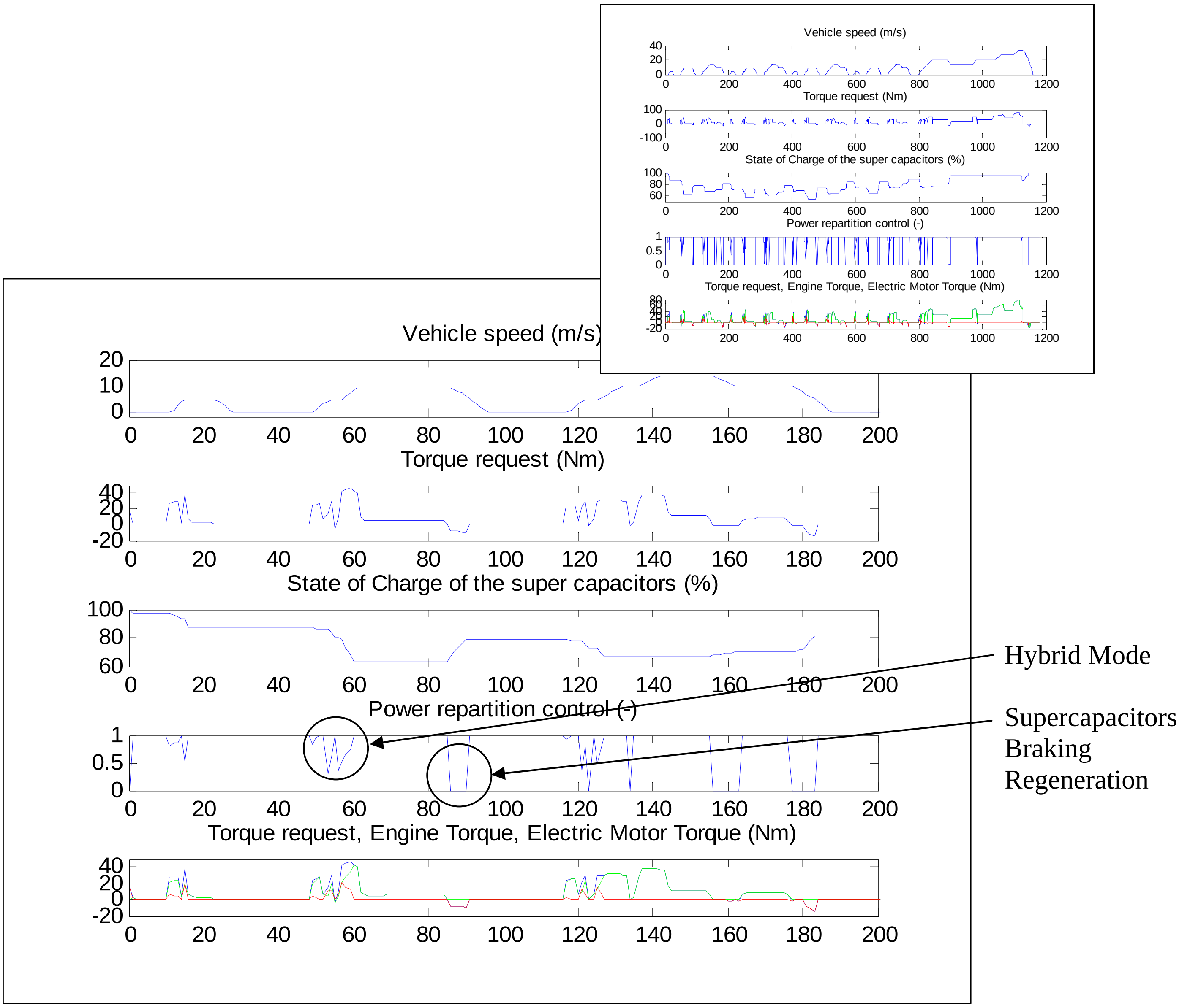
From Bellman principle, the minimum cost $V(X(k),k)$ at the time step *k*, $0 \le k \le N-1$, is then expressed as follow :

$$V(X(k),k) = \min_{u(k)} (L(X(k),u(k),k) + V(f(X(k),u(k)),k+1)) \tag{8}$$

u(k) subject to (5) and (6)

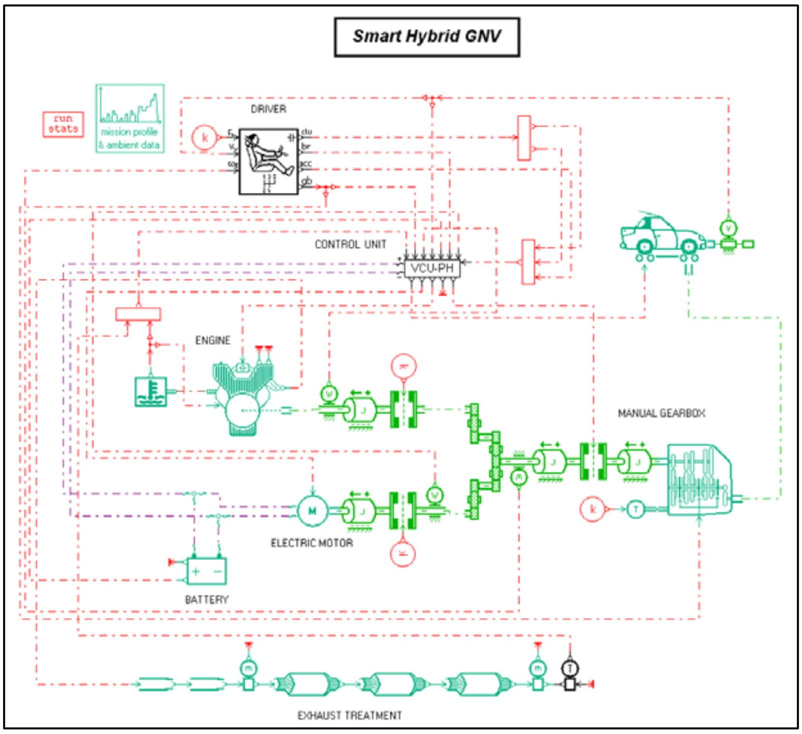
f being the function that modelizes the supercapacitors dynamics (cf (2)). This optimisation problem is solved backward from final time step using a discretization of function V in the state space.
It allows a fast optimization (N-1 optimization problem of 1 parameter to be solved) with a fine time discretization of the controller : it furnishes the optimal power repartition at each time step regarding fuel consumption with constraints on the battery state of charge. The gear shifts can also be optimized in this approach.

■ This approach is applied on a Natural gas engine, coupled with a starter alternator (a mild hybrid powertrain). The optimal power repartition obtained, for the NEDC Cycle, is displayed in the following figures :



In future work, other constraints on temperature should be introduced to take into account the activation of the catalytic converter and minimize also the pollutant emissions.

The resulting optimal power repartition is then integrated in AMESim model (displayed in next figure) via the supervisory controller which translates the driver requests (acceleration, braking, gear shift) in couple requests for the engine and the electric motor.



With this methodology, several architectures are simulated in AMESim and the associated potential reduction of consumption and/or of pollutant emissions are compared. Different types of engine (gasoline / diesel / natural gas) are also compared.

■ Real time control strategies are compared with these optimization and modelling results for the studied powertrain architectures in AMESim model. Different approaches are evaluated as fuzzy logic laws inferred from the optimization results, or the minimization of Equivalent Consumption Minimization Strategy [6] (ECMS: the battery being considered as an auxiliary reversible fuel reservoir, an instantaneous minimization of ECMS is performed). A third approach from the Pontryagin minimum principle is also tested.
To compare the different real-time control laws, we integrate the control system in a co-simulation framework : control model is running under Simulink, whereas the detailed engine, transmission model, and exhaust model are running under AMESim, using IFP Engine and Drive libraries.

■ Then, the control laws for a specific powertrain architecture will be implemented for a real-time use in a mild-hybrid compressed natural gas vehicle, developed by IFP, with a downsized turbo-charged Compressed natural gas (CNG) engine [7]. This vehicle is a Smart car equipped with a starter alternator and supercapacitors (Valeo Starter Alternator Reversible System, StARS)

A hardware-in-the loop (HIL) platform allowing real-time validation of control structure and strategies is being developed.
For implementation, an xPCTarget-based rapid prototyping system will be used for the vehicle.

References

[1] L. Guzzella, A. Sciarretta, *Vehicle Propulsion Systems, Introduction to Modelling and Optimization*, Springer, 2005.

[2] P. Menegazzi, P. Aubret, P.-L. Vernhes, *Conventional and Hybrid Vehicle Emission, Fuel Economy and Performance Analysis System Simulation* - FISITA congress, Barcelone. F2004F418 paper. Mai 2004.

[3] J.C. Dabadie, P. Menegazzi, R. Trigui, B Jeanneret, *A New Tool for Advanced Vehicle Simulations* - ICE 2005 - 7th int. conf. on engines for automobiles, Capri - September 2005.

[4] D. P. Bertsekas, *Dynamic programming and optimal control*, Athena Scientific, 1995.

[5] B. Wu, C-C. Lin, Z. Filipi, H. Peng, D. Assanis, *Optimization of Power Management Strategies for a Hydraulic Hybrid Medium Truck*, Proceeding of the 2002 Advanced Vehicle Control Conference, Hiroshima, Japan, September 2002.

[6] G. Paganelli, T.M. Guerra, S. Delprat, J.J. Santin, M. Delhom, E. Combes, Simulation and assessment of power control strategies for a parallel hybrid car, Journal of automobile engineering, IMechE, SAE International IEE, n°214, p 705-718, 2000.

[7] R.Tilagone, and S. Venturi, *Development of natural gas demonstrator based on an urban vehicle with a downsized turbocharged engine*. – IFP – Which Fuels for Low CO2 Engines? IFP International Conference/Les Rencontres scientifiques de l'IFP, P. Duret, X. Montagne, Eds., pp. 145-155. Éditions Technip, Paris, 2004.