Stratégie basée sur la commande prédictive du moteur à combustion pour les véhicules hybrides série-parallèle (HEV)

Model-Based predictive control strategy of the engine for the series-parallel hybrid vehicles (HEV)

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Soumis le : 28/09/2016 *Révisé le : 24/06/2017* *Accepté le : 28/06/2017*

ملخص

هذه الدراسة تركز بشكل خاص علي التحسين والتحكم في المحرك الخاص بالسيارات الهجينة المتوالية-الموازية (HEV). هذا النوع من التهجين مثيرة للاهتمام من حيث الأهداف ولكن معقدة على مستوى تحسين الأداء. لهذا فإننا بحاجة إلى دقة أكثر صرامة على تقريب النموذج، اختيارنا كان النموذج الخطي الذي تحصلنا عليه باستعمال طريقة التعرف SUBSPACE. التحكم التنبؤي أستعمل كمثبت لسرعة محرك الاحتراق, ثم سيتم تطبيق استراتيجية التحكم الإجمالي على مستوى النمط المنطقي لتحسين استهلاك وقود السيارات وكذا الحد من انبعاثات NOx الضارة بالبيئة. ان استخدام المحاكي "Hybrid Electrical Vehicle Model Balance Fidelity and Speed (HEVMBFS)", و استراتيجية التحكم أدى للحصول علي نتائج مشجعة للغاية.

الكلمات المفتاحية: سيارة الهجينة المتوالية-الموازية - النموذج الخطي - النموذج اللاخطي - محرك الديزل – نموذج محرك الاحتراق - محاكي HEV - التحكم التنبؤي - استراتيجية التحكم.

Résumé

Cette étude porte essentiellement sur l'optimisation et la commande du moteur thermique conçu pour les véhicules hybrides séries-parallèles (HEV), ce type d'hybridation est intéressant au niveau des objectifs mais complexe au niveau de l'optimisation des performances. Pour cela on impose une rigueur des plus sévères quant à l'approximation du modèle, Notre choix s'est porté sur un modèle linéaire obtenu par la méthode d'identification SUBSPACE. La commande prédictive est utilisée comme un régulateur de vitesse du moteur thermique, ensuite une stratégie de commande globale sera appliquée au niveau du mode logique permettant d'optimiser la consommation du carburant du moteur à combustion et par-delà réduire les émissions NOx nuisible à l'environnement. L'utilisation du simulateur «Hybrid Electrical Véhicule Model Balance Fidelity and Speed (HEVMBFS)» ainsi que la stratégie de commande ont permis de dégager des résultats assez encourageants.

Mots clés: *Série-Parallèle hybride véhicule - Modèle non linéaire - Modèle linéaire - Moteur diesel - Modélisation du moteur - Simulateur HEV - Commande prédictive - Stratégie de commande.*

Abstract

The main purpose of this work is the optimization and control of Series-Parallel Hybrid Vehicles (HEV) engines. This type of hybridization is interesting to achieve, but complex when the performance optimization is involved. The latter requires that the approximation of the model must be done with big care. The proposed model is a linear type obtained by SUBSPACE identification method. The engine speed controller uses predictive strategy, and the control law will be applied to optimize the engine fuel consumption and to reduce the environmentally harmful NOx emissions. The use of the simulator "Hybrid Electrical Vehicle Model Balances Fidelity and Speed (HEVMBFS)" and the global control strategy make it possible to achieve encouraging results.

Key words: *Series parallel hybrid vehicle - nonlinear model - linear model - Diesel engine - Engine modelling - HEV simulator - Predictive control - Control Strategy.*

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1. INTRODUCTION

The aim of this study is to improve the performance of hybrid electric vehicle (HEV), by reducing the energy consumption. Many research have applied the classic control tools to exploit the fuel economy potential, such as PID and LQR controllers. As example, the engine speed control used in HEVMBFS simulator is a PI controller (see website in reference). The latter produces unnecessary efforts that can cause the engine untimely accelerations; this may strongly undermine the engine performance in the long run. Moreover, the LQR controller is used for controlling idle speed only [1]; the authors have not tested the LQR controller in the New European Driving Cycle (NEDC). There is no ability In the PID and LQR controllers, to anticipate future events and to take control actions accordingly, as model predictive control (MPC). A large number of implementation algorithms have been presented in literature such as extended prediction self-adaptive control (EPSAC) [2], generalized predictive control (GPC) [3] and unified predictive control (UPC) [4]. Most of these control algorithms use an explicit process model to predict the future behaviour of a plant and because of this, the term model predictive control (MPC) is often employed. To overcome the weakness of the classical PID and LQR controllers, we use a model predictive controller (MPC).

The physical engine model, based on both thermodynamics and mechanics principles, is strongly nonlinear, which is very difficult to control. Though, there exist several methods for the identification of nonlinear systems, in the present study subspace methods for identification are used. The MPC controller will be tested under NEDC, with the aim of maintaining the necessary power level for a comfortable driving of the hybrid electric vehicle, by eliminating unnecessary effort which is produced by classic controllers and optimizing the consumption quantity. Finally, given the choice of the control being established to reach an appreciable level of performance, it will be necessary to improve the optimization strategy of the operating modes in order to obtain the lowest possible level of consumption, [5, 6, 7].

2. ARTITECTURE OF HYBRID VEHICLE:

Unlike the traditional cars which run on fuel, the hybrid car runs with thermal and electric engine; it thus calls upon two storages of distinct energies: storage of electrical energy (battery) and storage of fossil energy (fuel). The hybrid car is also an ecological car which aims to limit the polluting emissions in order to protect our environment [8]. Three main architectures are distinguished: series, parallel and series-parallel architectures. In this paper we focus on the series parallel hybrid vehicle with a structure represented in figure 1.

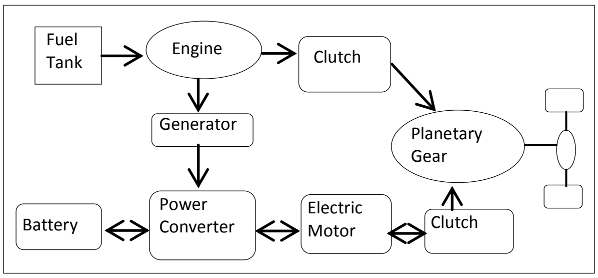

Figure 1 : Structure of series-parallel HEV.

The series-parallel system in figure 1 is composed of an electrical motor, a thermal engine and a generator, a control module of the supply (reverser/converter) and a distributer of energy. This structure combines both the advantages of series and parallel structures. In fact the system is characterized by the possibility of operating in series and parallel [9].

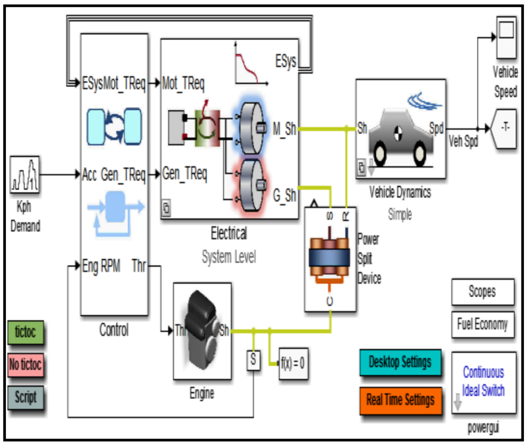

Figure 2 : The HEV simulation diagram.

The used is simulator HEVMBFS Shown in Figure 2 which describes the flowchart between different parts for modelling the HEV engine. The simulator contains a model of Series-Parallel Hybrid Vehicle, by SimElectronics, SimDriveline, Simscape and SimPowerSystems tools [10]. This can be downloaded for free from the official website of Matlab software.

In spite the advantages that this type of architecture offers, it will be necessary to control the total consumption of the engine. This objective will be reached by the design of a model which best approaches the process behaviour.

3. SUBSPACE-BASED IDENTIFICATION METHODS

In the early 1990's, a new type of system identification algorithms, called subspace methods, was introduced to the automatic control engineering community for the identification of multivariable linear time-invariant (LTI) systems. Mostly, these methods present a good alternative to the classical nonlinear optimization-based prediction error methods [11]. Subspace methods do not require an explicit parameterization of the system; this makes them numerically attractive and especially suitable for multivariable systems. Subspace methods can also be used to generate an initial starting point for the iterative prediction-error methods. This combination of subspace and prediction-error methods is a powerful tool for determining an LTI system from input and output measurements [12, 13].

Linear subspace identification methods are concerned with systems and models of the following form:

$$x_{k+1} = Ax_k + Bu_k + w_k \qquad (1)$$

$$y_k = Cx_k + Du_k + v_k \qquad (2)$$

With

$$E = \left[\begin{pmatrix} w_p \\ v_p \end{pmatrix} \begin{pmatrix} w_q^T & v_q^T \end{pmatrix} \right] = \begin{pmatrix} Q & S \\ S^T & R \end{pmatrix} \delta_{pq} \geq 0 \qquad (3)$$

The vectors $u_k \in R^{m\times 1}$and $y_k \in R^{l\times 1}$ are the measurements at time instant k of m inputs and l outputs of the process. The vector x_k is the state vector of the process at discrete time instant k, $v_k \in R^{l\times 1}$ and $w_k \in R^{n\times 1}$ are unobserved vector signals, v_k is called the measurement noise and w_k is called the process noise. It is assumed that they are zero mean, stationary white noise vector sequences and uncorrelated with the inputs u_k. $A \in R^{n\times n}$ is the system matrix, $B \in R^{n\times m}$ is the input matrix, $C \in R^{l\times n}$ is the output matrix while $D \in R^{l\times m}$is the direct feed-through matrix. The matrices $Q \in R^{n\times n}$, $S \in R^{n\times 1}$ and $R \in R^{l\times 1}$ are the covariance matrices of the noise sequences w_k and v_k.

4. MODEL PREDICTIVE CONTROL

Model predictive control (MPC) techniques have been recognized as efficient approaches to improve operating efficiency and profitability [14, 15]. This advanced method has the ability to anticipate future events and can take control actions accordingly. LQR and PID controllers do not have this predictive ability. Model Predictive Control is multivariable control algorithm that relies on dynamic models of the process [16], most often linear empirical models obtained by system identification [17, 18]. A cost function J is minimized in order to obtain the optimum control input [19]. The optimization cost function is given by:

$$J(z_k) = \sum_{i=0}^{p-1}\{[e_Y^T(k+i)Qe_y(k+i)] + [e_u^T(k+i)R_u e_u(k+i)] + [\Delta u^T(k+i)R_{\Delta u}\Delta u(k+i]\} + \rho\, k^2 \quad (4)$$

Without violating constraints (low/high limits), with:

$$e_y(i+k) = S_y^{-1}[r(k+i+1|k) - y(k+i+1|k)] \quad (5)$$

$$e_u(i+k) = S_u^{-1}[u_{target}(k+i|k) - y(k+i|k)] \quad (6)$$

$$\Delta u(k+i) = S_u^{-1}[u(k+i|k) - u(k+i-1|k)] \quad (7)$$

$$z_k^T = [u(k|k)^T\ u(k+1|k)^T \dots u(k+p-1|k)^T{}_k] \quad (8)$$

The effectiveness of this method is mainly due to the fact that, for a known or pre-calculated reference trajectory (at least on a certain horizon), it is possible to fully exploit information of preset trajectories located in the future.

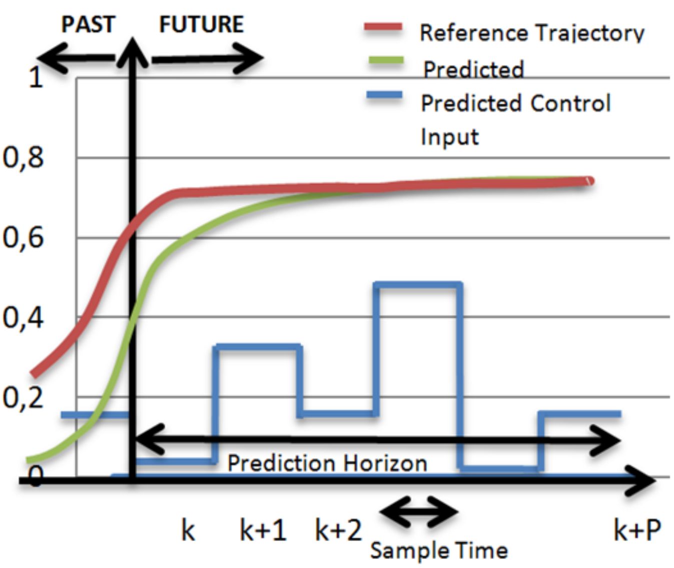

Figure 3 : A discrete MPC scheme.

The aim of the predictive strategy is to make the fitting between the process output and the predetermined reference trajectory on a finite horizon in the future, as illustrated on the diagram of figure 3. Thus, this method appears very suitable to deal efficiently with the problems of reference and especially trajectory tracking.

5. PID CONTROLLER

The HEV simulator uses PID controller to control the engine speed, then the simulation results will be compared with those of the proposed model predictive control.

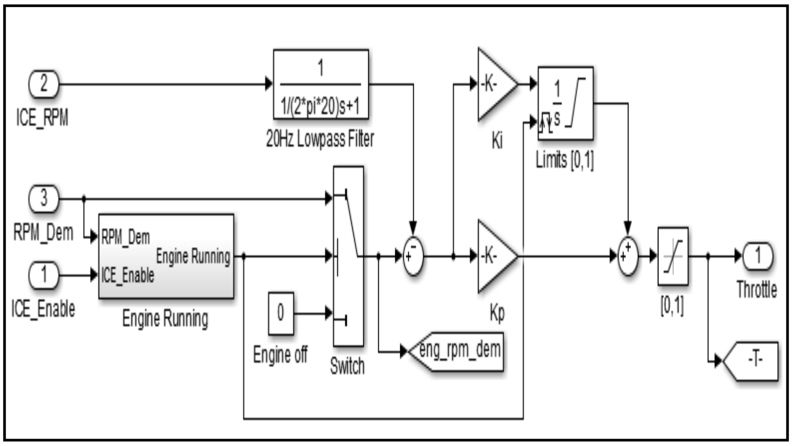

Figure 4 : Engine speed controller.

In figure 4, when the speed demand is set to zero, the idle speed is at 800 rpm. The PID controller parameters are tuned to give the optimal performance: KP = 0.02, Ki = 0.01, kd = 0. These parameters were obtained from HEVMBFS simulator.

6. SIMULATION RESULTS

Simulation tests were conducted in Matlab/Simulink environment. The results of PID controller are represented in figure 5 and 7. Whereas the results of the model predictive control are shown in figure 6 and 8.

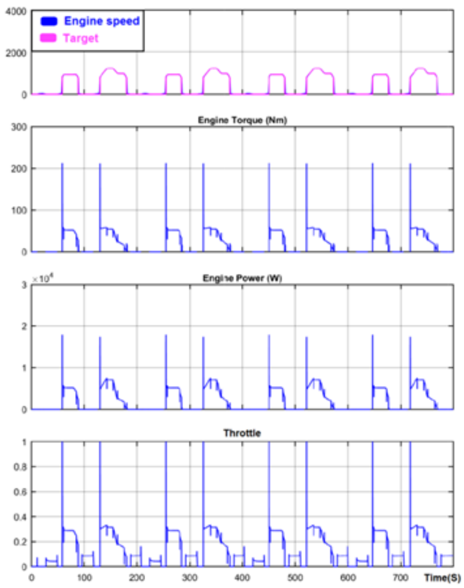

Figure 5 : PID controller simulation results in urban driving cycle (UDC standards).

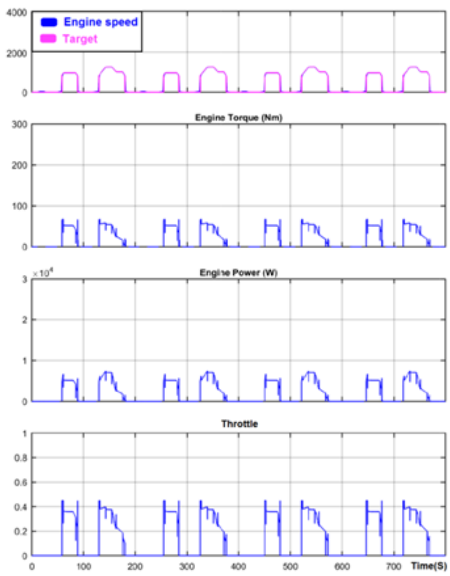

Figure 6 : model predictive control simulation results in urban driving cycle (UDC standards).

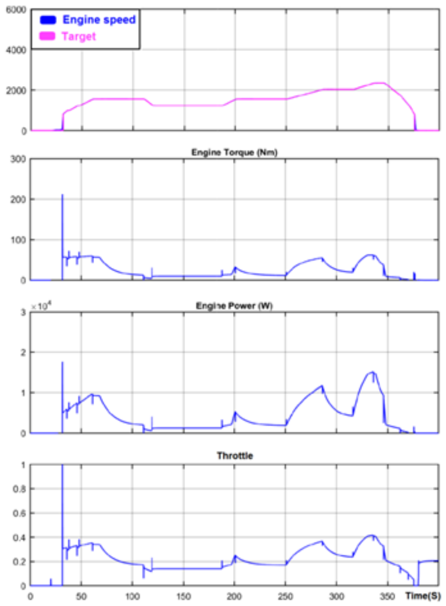

Figure 7 : PID controller simulation results in extra urban driving cycle (EUDC standards).

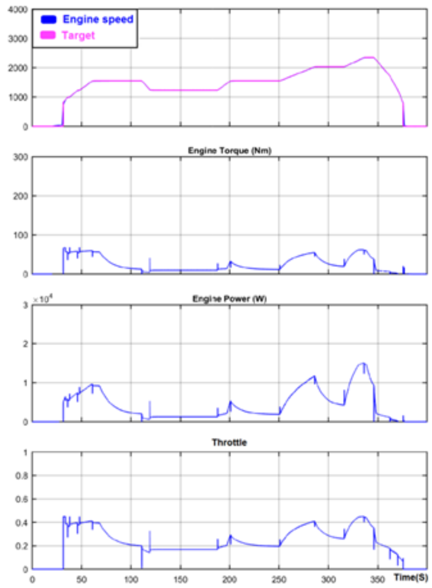

Figure 8 : model predictive control simulation results in extra urban driving cycle (EUDC standards).

Figure 5 and 6 represent the reel engine speed (rpm), the engine speed target, the engine torque (Nm), the engine power (W), and the throttle, using PID controller, and model predictive control respectively. Tested on cycle 1 which is an urban driving cycle (UDC standards) repeated four times, the vehicle reaches a maximum speed of 50km/h. figure 7 and figure 8 represent the reel engine speed (rpm) and the engine speed target, the engine torque (Nm),the engine power (W), the throttle using PID controller, and model predictive control respectively. Tested on the cycle 2 which is an extra urban driving cycle (EUDC standards), it reaches a top speed of 120 km/h.

It is noticed that the engine undergoes untimely accelerations and is submitted to unnecessary effort which is produced by PID controller output action. This may strongly undermine the engine performance in the long run (Fig. 5 and 7). In contrast, the predictive controller generates appropriate action signal with reduced effect on the engine demand. The magnitude of the controller action is well lower than that of the PID controller. Moreover, it is observed that the action of the MPC controller is generated just when required to follow the various reference cycles and is null at idle time. It is thus clear that the model predictive control is more advantageous, see figure 6 and 8. The proposed controller could be well recommended for use in such control strategy. The parameters used in the MPC control are: Sampling time ‘t = 0.005’, Prediction Horizon ‘u1 = 2’, Control Horizon ‘u2 = 10’, and the constraints of the imput system (Throttle): ‘Umin = 0’, ‘Umax = 1’, the constraints on the output system (Engine Speed): ‘Smin = 800’, ‘Smax = 4500’.

7. MODE LOGIC

For efficient power management, an understanding of the economics of managing the power flow in the system is required. For example, during deceleration, the kinetic energy of the wheels can be partially converted to electrical energy and stored in the batteries. This implies that the system must be able to operate in different modes to allow the most efficient use of power sources [20, 21, 22].

The Stateflow® chart which is a realization of the conceptual framework shown in figure 9 has two notable differences. The “acceleration” and “cruise” states have been grouped to form the “normal” super state, and the “low speed/start” and “normal” states have been grouped together to form the "motion" super state. This grouping helps organize the mode logic into a hierarchical structure that is simpler to visualize and debug.

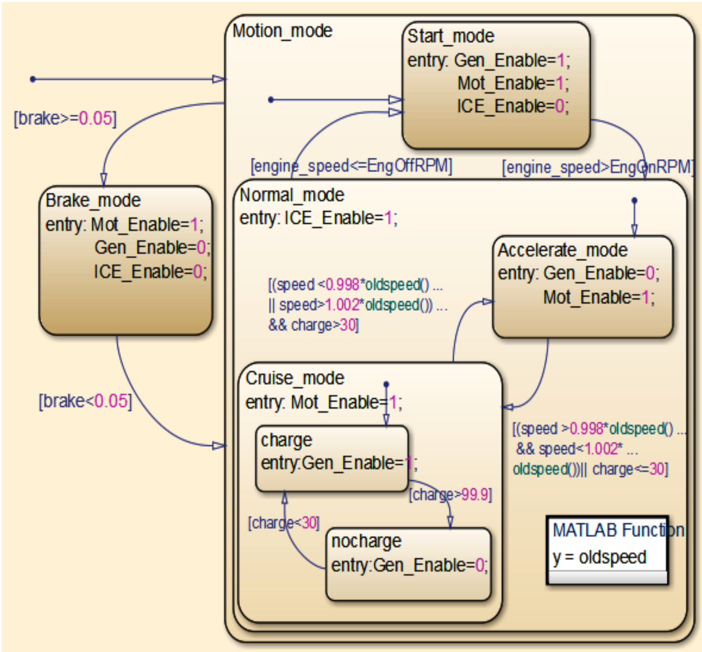

Figure 9 : Mode logic modelled with Stateflow®.

The State flow® model produces three outputs that lead to Motor, Generator, and Engine control systems. However, by default, those signal connections do not affect the output of those control systems. For that we must connect the State flow® to the rest of the model. Each subsystem has a manual switch in it which allows selecting a signal that uses the Stateflow® output to enable or disable the output of the PI controller.

In order to assess the emission levels of the engine, and fuel economy in hybrid vehicle (HEV), we use New European Driving Cycle (NEDC standards). The latter is composed of two parts: UDC (Urban Driving Cycle) repeated 4 times, is plotted from 0 s to 780 s and EUDC (Extra Urban Driving Cycle) is plotted from 780 s to 1180 s.

After enable mode logic is switched on, the obtained results are shown in figures 10, 11 and 12.

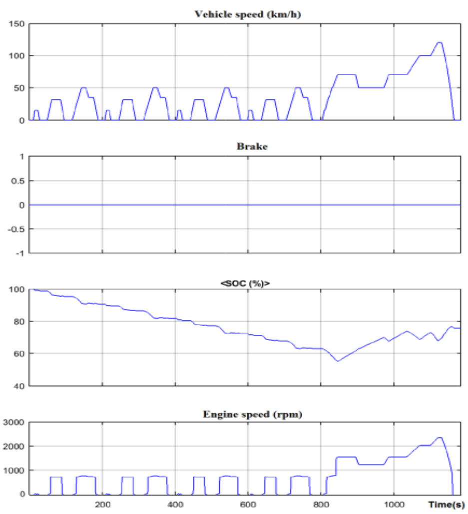

Figure 10 : Mode logic inputs.

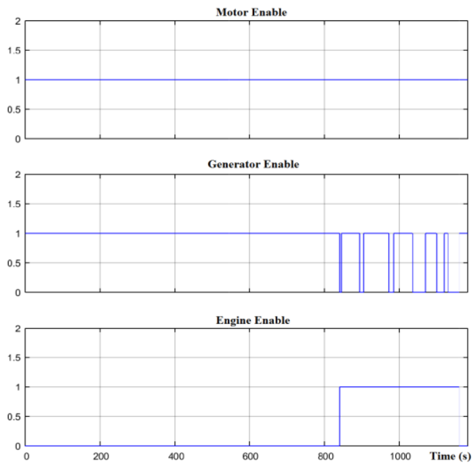

Figure 11 : Mode logic outputs.

The mode logic has four inputs (vehicle speed, brake, charge and engine speed) shown in figure 10, and three outputs connected to controllers of motor, generator and engine shown in figure 11, the output is logic, 0 for disable and 1 for enable.

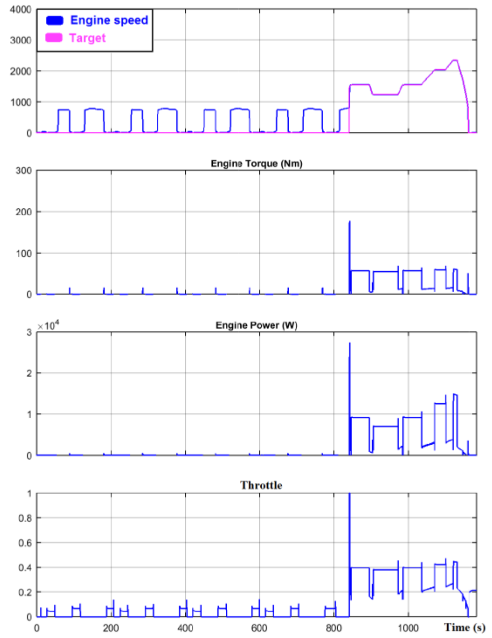

Figure 12 : Results obtained on New European Driving Cycle (NEDC standards) with enable mode logic.

Using the mode logic from HEV simulator, we notice that the engine is enabled only in ultra-urban cycle figure 11 and 12. We also note that the peak appeared in throttle, appears also in engine torque and power figure 12. The fuel consumption is 2.146 L/100. These results are obtained using mode logic and PID controller from HEV simulator, the last results will be compared with the enhanced mode logic and model predictive control, to gain more fuel economy and get better performance.

8. ENHANCED MODE LOGIC:

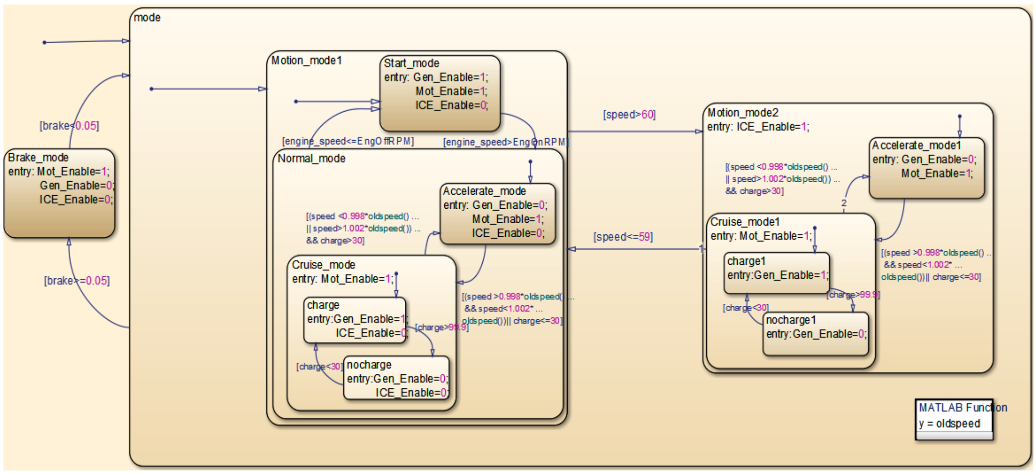

Figure 13 : Enhanced mode logic modeled with Stateflow®.

In the enhanced mode logic we propose two motion modes: the first mode, called Motion_mode1, which can reach a maximum speed of 60 km/h and a second mode, called Motion_mode2, starting from a minimal speed of 60 km/h to a maximum speed of 120 km/h. The ‘acceleration’ and ‘cruise’ modes have been combined into one mode known as the normal mode, which can be further combined with the ‘low speed/start’ to form the Motion_Mode. Through this structure, a hierarchical framework of the enhanced mode logic is obtained which is easier to visualize and debug. This grouping is also applied to the modes of Motion_Mode2, The enhanced mode logic is programmed under Matlab/Stateflow® shown in figure 13.

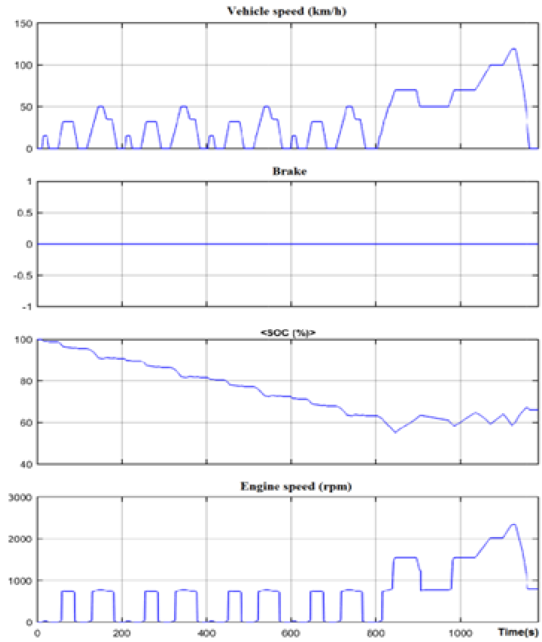

Figure 14: Enhanced mode logic inputs

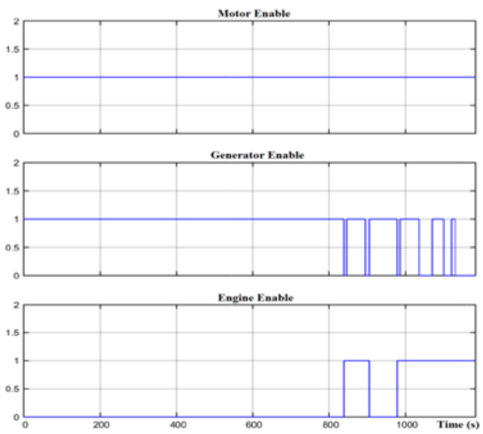

Figure 15 : Enhanced mode logic outputs.

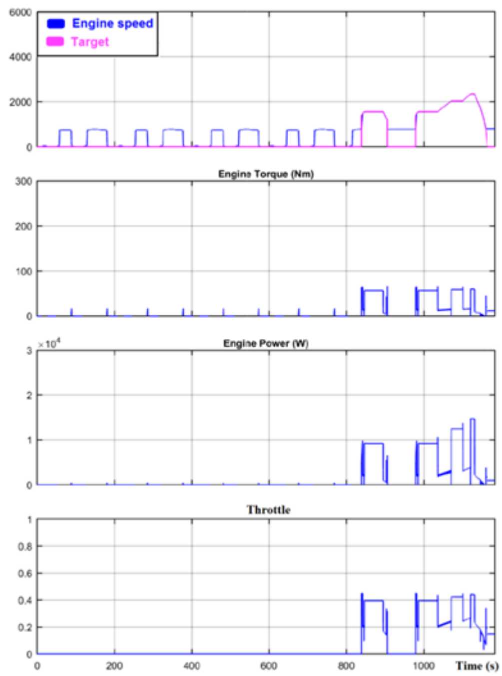

Figure 16 : Results obtained on New European Driving Cycle (NEDC standards) with enable enhanced mode logic.

Enhanced mode logic has four inputs (vehicle speed, brake, charge and engine speed) shown in figure 14, and three outputs connected to controllers of motor, generator and engine as shown in figure 15, the output takes on logic value, 0 for disable and 1 for enable. Using the enhanced mode logic, we notice from figure 15 and 16 that the engine is enabled only when the speed is above 60 km/h. We also notice that the peaks disappeared in throttle MPC and also in the engine torque and power figure 16. The fuel consumption is 2.002 L/100. These results are obtained using enhanced mode logic combined with MPC.

Table 1 : Fuel Economy on New European Driving Cycle (NEDC standards).

	Mode logic disable		Mode logic enable		Enhanced mode logic enable	
Controller	PID	MPC	PID	MPC	PID	MPC
Liter/100	2.509	2.5	2.146	2.13	2.024	2.002
Km/Litre	38.85	40	46.6	46.95	49.4	49.96
MPG	93.74	94.1	109.6	110.4	116.2	117.5
Total Fuel Used (L)	0.2743	0.2733	0.2346	0.2328	0.2213	0.2188

The table 1 shows the different consumption quantities in the New European Driving Cycle (NEDC standard). It is noticed that by using MPC controller, accompanied or not by the two various logic modes, the fuel consumption remains lower than that obtained by the PID controller. Also, the introduction of enhanced mode logic optimizes better the consumption quantity. It should be noted that the fuel saved in the new control strategy so little, remains appreciably important when considering the number of kilometres traversed by the vehicles around the world. We may therefore conclude that the enhanced mode logic with model predictive control are more powerful and optimal, for reducing the fuel consumption thus reducing NOx emissions that are harmful to the environment.

9. CONCLUSION

Due to the development of rigorous methodologies for the design of models and powerful algorithms of control and optimization, we used the subspace method to obtain an acceptable model of the thermal engine. This model has been the subject of the application of the predictive control. It is noticed that the results of simulation under various scenarios for different cycles are satisfactory. This may allow us to assert that the MPC controller fulfils well the objectives stated at the beginning, namely reduced fuel consumption, a more comfortable driving and increased longevity of the HEV vehicle equipment. The Introduction of a new optimization strategy of the operating modes allowed substantially improving the economic indices, reducing the energy consumption, considering the environment and reducing NOx emissions as well. Finally, this work opens the way for research in the three parts treated in order to satisfy even more the performance criteria of the series-parallel hybrid vehicle HEV.

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- **Website:**

The HEVMBFS simulator can be downloaded for free from the official website of Matlab software:

https://www.mathworks.com/matlabcentral/fileexchange/28441-hybrid-electric-vehicle-model-in-simulink?requestedDomain=www.mathworks.com

Date of the last consultation: 17/05/2017

NOMENCLATURE

k: Current control interval.

ρ: Prediction horizon (number of intervals).

$Q(n_u - b_y - n_u)$, R_u, $R_{\Delta u}(n_u - b_y - n_u)$: positive-semi-definite weight matrices.

S_y: Diagonal matrix of plant output variable scale factors, in engineering units.

S_u: Diagonal matrix of MV scale factors in engineering units.

$r(k+1|k)$: n_y plant output reference values at the ith prediction horizon step, in engineering units.

$y(k+1|k)$: n_y plant outputs at the ith prediction horizon step, in engineering units.

z_k: QP decision.

$u_{target}\ (k+i)$: n_u MV target values corresponding to $u(k+i|k)$, in engineering units.