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An optimized control strategy for hybrid electric vehicle

B. AMGHAR [1], I. EL ABBASSI [2], A-M. DARCHERIF[1]
[1]QUARTZ Laboratory EA 7393, ECAM-EPMI, Cergy, France
[2]LREE, , ECAM-EPMI, Cergy, France

Abstract—Hybrid Electric Vehicle (HEVs) are promising solutions for terrestrial mobility.. Their original "serial/parallel" architecture for the power path allows the advantages of both configurations. The main purpose of this paper is to present the design of a new hierarchical hybrid control for HEVs with a Petri Nets supervisor. The goal is to reduce the fuel consumption and optimize the battery solicitation. The components of the vehicle; including internal combustion engine, the driving machine, the generator machine, batteries and transmission, the vehicle's load model as well as the designed controller are modeled using Matlab/Simulink software. The simulations are performed in urban and highway driving cycles

Keywords: ***Petri Nets, Hybrid Electric Vehicle, hierarchical hybrid control supervisor*.**

I. INTRODUCTION

In the modern society, comfort and reliability of transportation systems have become an issue of competitiveness between cities. Mobility patterns are various and numerous. The design of the cities of the future should take into account the citizens behavior and needs in term of transportation, while ensuring a favorable ecological impact.

According to the European Environment Agency, road transport is the largest consumer of energy, with the most important part (around 72 %) relative to the total transport energy consumption (Doufene et al. 2014)[1]. The European Commission expects 1.6 billion vehicles in the world in 2030 and 2.5 billion in 2050. In addition, personal cars can have worrisome ecological consequences. Personal cars using internal combustion engines (ICE) are responsible for 10% of CO2 emissions in the atmosphere (Doufene et al. 2014). These emissions know a steady increase, despite the advancements in related vehicle technology. The extent of such influence on climate is still a matter of debate. Our paper deals with one of the technological breakthroughs that hold significant potential towards a cleaner planet: electrified power train technology [2]. This technology would be a significant contribution to the international policies for sustainable development by reducing CO2 emissions and non-renewable energy consumption [3].

In this research, we are interested in particular in Toyota Prius vehicle model (More than 5.125 million hybrids were sold by Toyota Motor Company worldwide through March 2013 (TPR 2013) indeed)[4]. This model is based on the Serial / Parallel coupling of the Engine Motor, the Generator Motor and Electric Motor. The first generation Prius, at its launch, became the world's first mass-produced gasoline-electric hybrid car. At its introduction in 1997, it won the Car of the Year Japan Award, and in 1998, it won the Automotive Researchers' and Journalists' Conference Car of the Year award in Japan [6].

The contribution of this work is to study how to control the power flow of the vehicle in an optimal possible way. In other words, this paper examines the optimal control of energy flow, also known as the optimal control strategy and management of the electrical energy of the vehicle. The proposed line of study is to develop the best control strategies using Petri nets in order to optimize the vehicle range and energy flexibility. The first part of this paper presents the modeling of different parts of the hybrid electric vehicle. Following the vehicle model, a control strategy is proposed based on Petri Nets and optimization algorithms. The results show that our approach provides outstanding performance and better management of electrical energy in the vehicle.

II. SYSTEM MODEL

The Toyota Hybrid Electrical Vehicle (THEV), or sometimes known as the Synergy Drive, is the first commercial vehicle with a power-split hybrid design [2][3]. As shown in Fig.1, there is a single planetary gear set [12]. The sun gear is connected to the Generator Motor, the carrier gear is connected to the engine, and the ring gear is connected to the Electrical Motor and to the vehicle through a gear ratio.

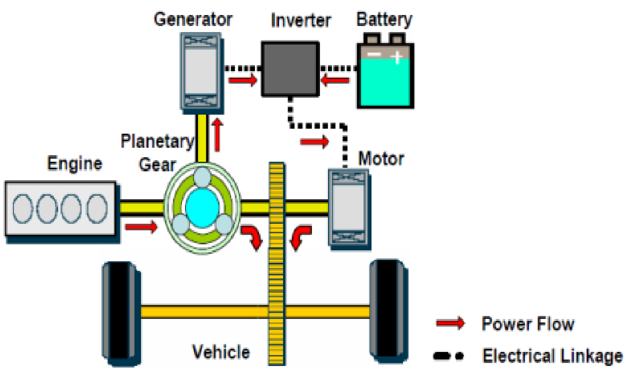

Fig.1. Series–parallel VEH architecture

Diesel Engine Model

A diesel engine like any other engine is comprised of various components and systems. Today's engines are much more complex in structure and have an advanced design due to their highly improved performance, efficiency and much lower emissions than their ancestorsFig.2.

In this work, the engine simulation model is simplified to

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accommodate the need of top-level control strategy design.

Fig.2. Diesel engine motor

A lookup table of wide-open-throttle (maximum) engine brake torque versus engine speed is directly derived from the engine brake specific fuel consumption map which was generated from experimental data obtained in Lay Automotive Laboratory at the University of Michigan, for more details about this BSFC map data, see [2] and [3]. The instantaneous engine torque is approximately decided by the following equation:

$$T_e(\omega_e) = uT_{e,max}(\omega \qquad (1)$$

Here, is a nominal control signal adjusting the engine throttle position and therefore the output engine torque, it take values in the interval $[0,$ with 0 and 1 indicating closed-throttle and wide-open-throttle position, respectively . $T_{e,max}(\omega$ is the is the maximum available engine brake torque which is a function of the engine speed and described by the look up table of wide-open-throttle engine brake torque. is the the motor speed

The rate of the engine speed change is expressed by:

$$\frac{d\omega_e}{t} = \frac{(T_e(\omega_e) + T_{epm}(\omega}{(J_e + J_{epm})} \qquad (2)$$

Here, $T_{epm}(\omega$, a signed vector, is load torque determined by the engine pump/motor. and $J_{ej}$are engine and engine pump/motor inertia, respectively. If the engine speedrises above the maximum speed, the engine torque drops to zero. Additionally, a logic control module is added into the engine model in order to shut down the engine when not needed in series hydraulic hybrid propulsion configuration.

Battery Model

There are different methods for calculating the battery state of charge; the most classic is performed by coulometry. By convention generator, it is expressed by the following equations:

$$SOC_{batt}(\%) = SOC_{batt-ini}(\%) - \frac{100}{3600}\begin{cases}\int_0^t \frac{i_{batt}(t)d\tau}{C_n}, & \text{discharge } i_{batt} > 0 \\ \int_0^t \frac{i_{batt}(t)\,\eta\, d\tau}{C_n}, & \text{scharge} i_{batt} < 0\end{cases}$$

(4)

where SOC_{batt-} is the the initial state of charging and discharging, is the rated capacity; i_b is the battery current; is the efficiency of charging, not constant.

Fig.3. A hybrid car battery

Motor and Generator Model

The most adopted motors for HEV are AC induction motors and AC Permanent Synchronous Magnets Motor (PMSM) regulated by means of a field oriented control or direct torque control Serving as the source of supplemental motive force that provides power assistance to the engine as needed, the electric motor (EM) helps the vehicle achieve excellent dynamic performance, including smooth start-offs and acceleration. When the regenerative [10] brake is activated, Generator Motor GM converts the vehicle's kinetic energy into electrical energy, which is then stored in the HV battery Fig.4.

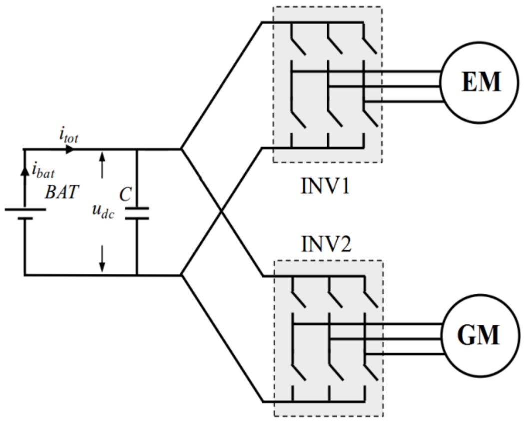

Fig.4. Power-split hybrid or series-parallel hybrid

Voltage equations are expressed as follows[9]:

$$\begin{cases} V\sin(\delta) = i_d R_1 + \omega i_q L_q \\ V\cos(\delta) = i_d R_2 + \omega i_d L_d + \end{cases} \qquad (5)$$

The motor torque is then obtained as:

$$T = \frac{3p}{2}(\Psi_M + (L_d - L_q)i_d \qquad (6)$$

Where and are the d-axis and q-axis components of the stator current vector.

III. HYBRID CONTROL

Dynamical systems are usually continuous or discrete or both. Dynamical Systems Continuous (SDC) has variables whose behavior continuous in time (voltage, current, speed, torque ....). They are often modeled by differential equations

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Volume 6, Issue 5, November 2016

or equations of state and transfer functions. For discrete dynamical systems (SDS), the space of output variables is a discrete set of Boolean value (state opening closing of a switch, number of switches open closed in a simultaneous static converter, number of pulses for controlling switches). Systems including both continuous characteristics and discrete are called hybrid dynamic systems. In a very simplified one SDH has two sub sets, a continuous block, a block discrete:

- The continuous block symbolizes the dynamic evolution of the state [8].

- The block has the discrete system is discrete event receives internal events, external conditions.

The overall objective of this paper is to define an operating strategy for an HEV using a hybrid hierarchical control. The results of this approach should define how the vehicle can decrease fuel consumption, while maintaining low vehicle emissions. Because of the hybrid system, just operating an engine in its regions of high efficiency does not guarantee efficient vehicle operation[5]. These results will not give the specific powertrain commands necessary to enable complete vehicle operation, and are meant only to define a literal strategy; that is, an understanding as to why the vehicle should operate in a certain way under given conditions.

The approach is a predictive calculator; it calculates the necessary configuration depending on the instantaneous demand and future information. If the car wanted to move from point A to point B with a known speed, GPS coordinates allow the system to calculate a route with reliefs(Fig.5a). Knowledge of slopes and distances allow the controller to calculate the best strategy for energy management by using both sources of energy.

The controller is based on a petri net supervision; the supervisor calculates the ideal configuration of the three subsystems; Thermal

Motor, Electrical Motor and Generator Motor, by taking into account the state of the battery and driving profile. At a lower level of the hierarchical control, optimization algorithms are used to calculate the reference input for each subsystem. To ensure a good tracking performance of the controlled outputs of each subsystem, a decentralized local controller is designed. Proportional integral derivative PID controller was used for the engine motor and two sliding mode controllers for the electric and generator motors (Fig.5b).

The command consists of three hierarchical parts; the first is based on a control loop PI controller for controlling the internal combustion engine and sliding mode control for electrical motor and generator motor. The second control is placed between the regulation loops of the subsystems and supervisor control based on Petri net [10],[11]. The supervisor regulator are synthesized by Petri net, the places P1, P2 and P4 respectively are modeling the state of the Thermic Motor, Electric Motor and Generator Motor. The transition from one place to another is dependent on the state of Acceleration demand, SOCbat and GPS coordination.

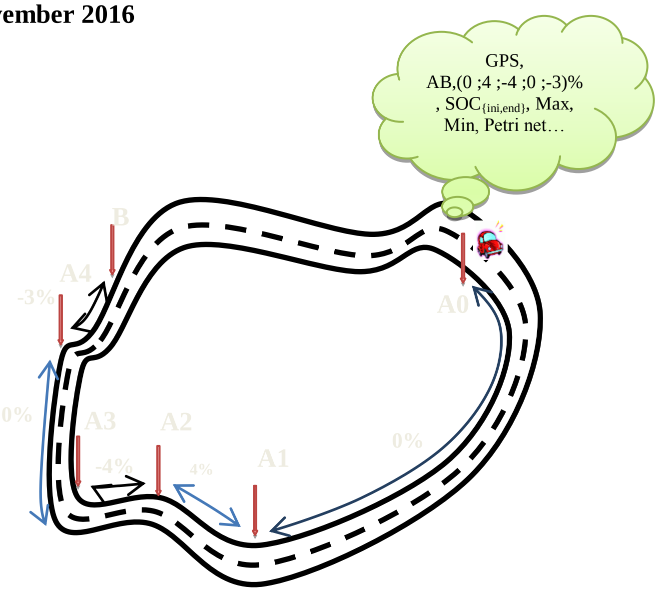

Fig.5a. Example of situation

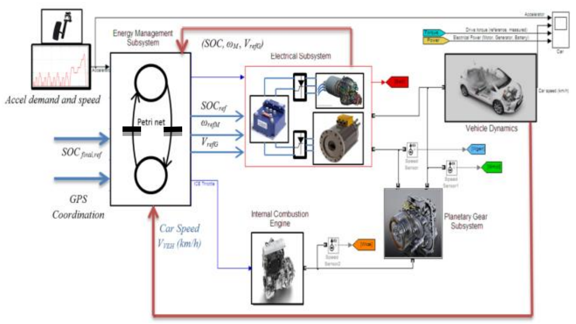

Fig.5b. Control Strategy

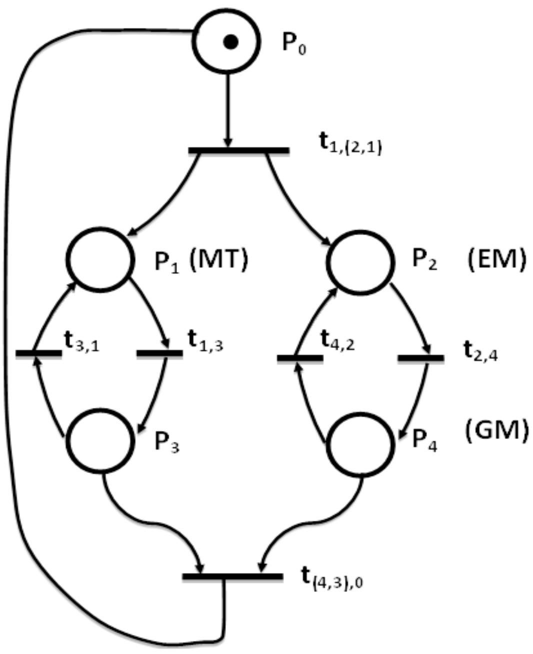

Fig.6.Petri Net Control

The significance of all places and transition is shown in Table I and II

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Table I Places and designations

Places P_i	**Designations**
$\mathbf{P_0}$	Stationary vehicle initial state
$\mathbf{P_1}$	Engine Motor state
$\mathbf{P_2}$	Electric Motor state
$\mathbf{P_3}$	Generator Motor state
$\mathbf{P_4}$	Auxiliary Place

Table II. Transitions and designations

Transition $t_{i,j}$	Designations
$t_{0,(1,2)}$	Car Keys contact is on
$t_{2,4}$	[(the vehicle is on a downhill slope)&& (**V_{VEH}> $V_{VEH, ref}$**) && (**SOC <SOC_{Max}**)] or[(**SOC <SOC_{Max}**) && Energy Recover <Necessary Energy to charge batteries]
$t_{4,2}$	[(the vehicle is on a downhill slope)&& (**V_{VEH}> $V_{VEH, ref}$**) && (**SOC<SOC_{Max}**)] or [(**SOC ≥ SOC_{Max}**) or (Energy Recover ≥ Necessary Energy to charge batteries)]
$t_{1,3}$	[(power demanded < power supplied by the Eelectricmotor) && (Energy demand ≥ Energy of batteries)]
$t_{3,1}$	[(power demanded < power supplied by the Eelectricmotor) or(Energy Recover ≥ Necessary Energy to charge batteries)]
$t_{(4,3),0}$	(Car Keys contact is on) &&(Accelerator pedal position = 0)

Even though a linear control approach is possible, as discussed in the previous section, the control algorithms used in many HEV prototype vehicles are rule-based. This is because of the multiple-input and multiple-objective nature of the control problem. It is intuitive that since the engine is the predominant power source and if we can operate the engine at an efficient manner, the overall vehicle efficiency will be reasonable. This simple idea is an easy way to provide a near-optimal solution quickly, even though there is no guarantee of its closeness to optimality. For engineers pressed for time, the rule-based design strategy is a safe approach.

As shown in the Figures (Fig.7, Fig.8, Fig.9), the driving force can be provided by motor and/or engine. When the power demand is low and the battery SOC is sufficiently high, the motor works individually to drive the vehicle [6].

As the vehicle speed increases, power demand increases, or the battery SOC becomes too low, the engine will be started to supply the power. The generator cooperates with the motor to help start the engine. Within the engine operating range, its engine power will be split through the planetary gear system. Part of the power goes to the vehicle driving wheel through the ring gear. The rest drives the generator to charge the battery and/or directly supply the motor power. In other words, although the engine fully supplies the power at this stage, the power is split and executed through two paths, the ring gear to the final wheel and the generator to the motor.

The Figures (Fig.6, Fig.7 and Fig.8) represent algorithms optimization and control strategy of hybrid electric vehicle. Fig.6 shows the thermal motor control algorithm, Fig.7 shows the controller of electric motor and Fig.8 represents the generator motor control algorithm. The main optimization algorithms are based on the state of charge of the battery (SOCbat) the power demand and the information transmitted by the Petri net [13].

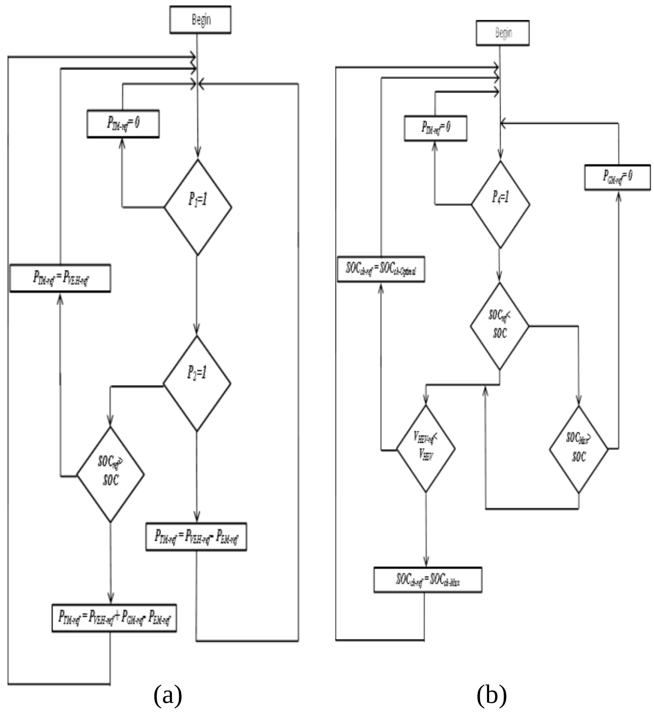

Fig.7. (a) Algorithm of optimization control of Thermal motor TM. (b)Algorithm of optimization control of generator motor GM

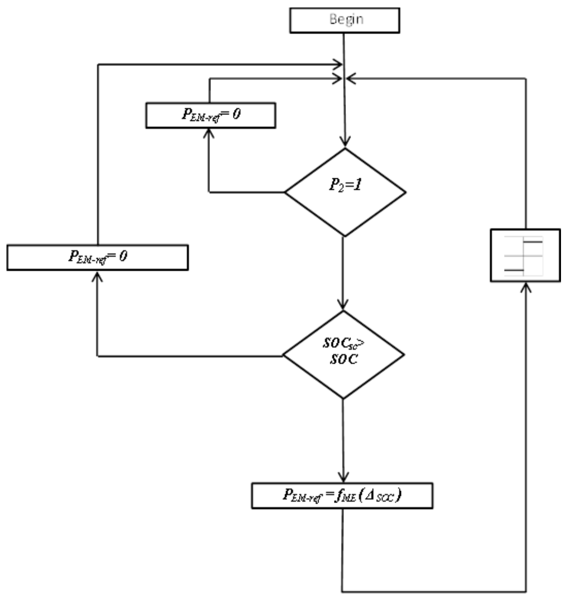

Fig.8.Algorithm of optimization control of electrical motor EM

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Volume 6, Issue 5, November 2016

IV. SIMULATION RESULTS

In this section simulation results are presented using MATLAB SIMULINK. The developed command is applied to a Simulink model of a hybrid electric vehicle that has a Series / Parallel architecture.

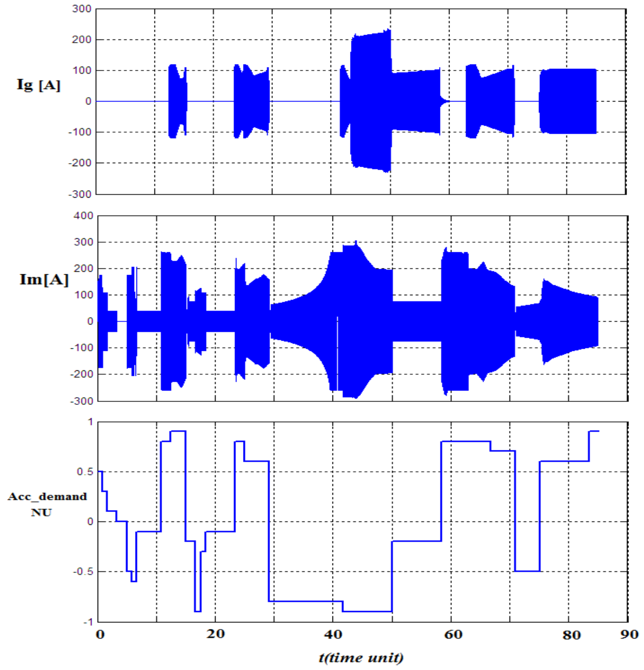

Fig. 9 Currents variations Ig generator motor and Im electrical motor.

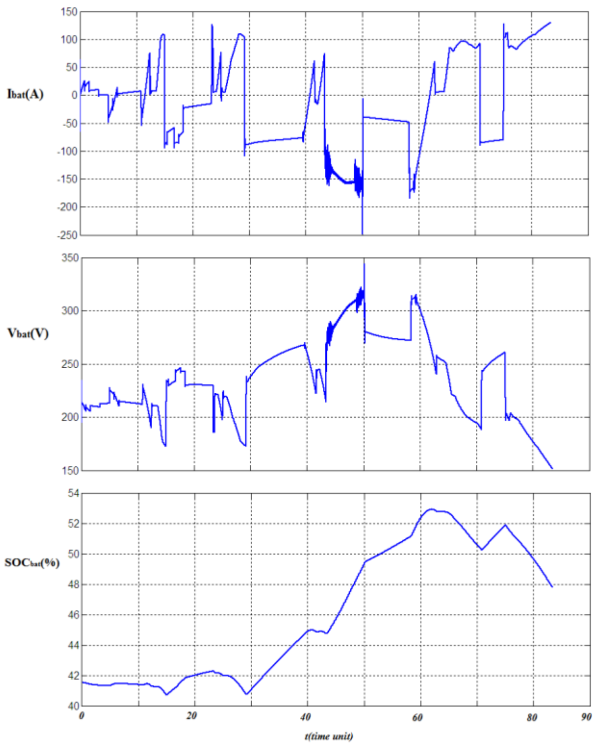

Fig 10. Charge (SOC_{bat}), voltage (V_{bat}), and current (I_{bat}) of Battery.

Figure 10 (a) shows the currents Ig of the motor generator and Im of the electric motor based on the calculated acceleration demand according to the road profile and GPS coordinate. We can remark that both systems are activated depending on the demand of acceleration and optimal calculators.

Figure 10 (b) shows the state of the current Ibat, the voltage Vbat and SOCbat battery according to the same profile demand acceleration.

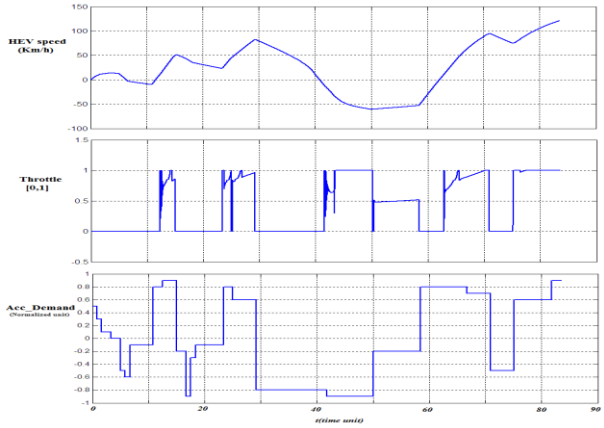

Fig.11. Speed (VHEV), throttle, and acceleration demand variations.

Figure 11 shows the vehicle speed and fuel usage [0.1] according to the acceleration request. It is clear that the fuel demand (Throttle) is variable and it depends on the situation of the vehicle and the algorithms developed in this article. The results showed the use of this control strategy saves 10% fuel (fuel gas emission reduction).

V. CONCLUSION

In this paper, a new hierarchical hybrid control strategy is proposed for the management of the energy flow in an HEV. The design of the controller is based on Petri networks, PID and sliding mode approaches with optimization algorithms. Simulations are performed to highlight the efficiency and the performances of the proposed control scheme. The obtained results show that the fuel consumption is reduced. It is clear that the recovery of energy and the use of the battery are optimal.

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