Real-Time Energy Management based on the Prediction of Hybrid Vehicle's Future States

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***Abstract*—This paper proposes an optimal predictive energy management strategy for hybrid vehicle. The proposed strategy is designed according to a hierarchical control layers. The highest level (third) can predict battery state of charge; vehicle power consumption; Internal Combustion Engine (ICE) and Electrical Motor (EM) current optimal efficiencies. In the second level, an optimal controller is developed to generate the optimal EM and ICE torques set points. Then, in the first level, there are robust controllers to regulate the set points of each vehicle subsystems. A MATLAB/TruckMaker simulation results show that the proposed strategy increases vehicle energy efficiency w.r.t. other strategy.**

I. Introduction

In recent years, rising gasoline prices and perceived fossil fuel overdependence have motivated interest in various types of more energy efficient alternative vehicles [1]. The Hybrid Electric Vehicle (HEV) has gained acceptance in the light-duty and commuter markets, but is ill suited for hauling loads, traversing very long distances, and continual stop-and-go operation. Due to conversion inefficiency and to the low power density limits of electric motors and batteries, typical average gains in fuel economy reaches only few percent. Hydraulic Hybrid Vehicle (HHV) technology is a viable alternative capable of outperforming a HEV under these conditions [2]. Unlike a HEV which stores energy generated through regenerative braking in a battery, the HHV recovers also energy in the form of pressurized hydraulic fluid stored in an accumulator dedicated for that purpose. The result is a highly efficient and power-dense hybrid system capable of capturing and reusing a substantially higher portion of braking energy than is possible with a HEV. HEVs provide unprecedented potential for increasing fuel efficiency while addressing tighter emission standards, particularly when a parallel configuration is used [3]. The untapped potential of hybrid powertrains may be realized through design and implementation of energy management control systems. Several methods for energy management and optimization aiming at the minimization of different cost functions have been published [4]-[10], such as dynamic programming [4], the equivalent consumption minimization strategy [5], Pontryagin's Minimum Principle (PMP) [6], model predictive control and adaptive equivalent consumption minimization strategy [7]. The Intelligent Hierarchical Hybrid Controller Strategy (IHHCS) in [8], [9], consists of three control level based on neural network, fuzzy logic and rule based optimization. An intelligent supervisory controller based on fuzzy logic in the third level, an intelligent power distribution controller based on neural fuzzy logic strategy in the second level and fuzzy controller in the first level. In addition, a fuzzy predictive control approach, combining fuzzy logic control and model predictive control, is proposed to improve the energy performance of HEV based on [10].

The desired contributions of the proposed work are twofold: The primary objective is to investigate and propose an accurate and reliable model of Hydraulic-Electric Hybrid Vehicle (HHEV) corresponding to the BUSINOVA bus[1]. Indeed, it is developed an accurate simulation model of the overall bus, based on mix between IPG automotive TruckMaker and MATLAB/Simulink software (cf. sections II and IV). This software has been chosen because it allows reliable and dynamic simulation of the overall bus and its different embedded and interconnected sub-systems (such as Electric Motor (EM), Hydraulic Motor (HM), Internal Combustion Engine (ICE), Hydraulic Pump (HP) and battery). The second main contribution corresponds to the proposition of an overall optimal energy management strategy based on the prediction of future bus states (cf. section III), in order to enhance its energy efficiency, leading therefore to minimize the total energy consumption (summation of electric energy and fuel energy). The proposed strategy consists of three control levels based on neural network. Prediction strategy using Adaptive Neuro Fuzzy Inference System (ANFIS) is developed in the third level (the highest level) to predict State of Charge (SOC) of the battery for the whole driving day and the power consumption of the vehicle over a given prediction time horizon. In addition, the current optimal efficiency for ICE and EM are also predicted in this level. In the second level, an optimal strategy is proposed to manage and optimize the power distribution between the two different sources. Then, in the first level (the lowest one), there are Local Fuzzy tuning Proportional-Integral-Derivative Controllers (LFPIDC) to regulate the set points of each vehicle sub-systems (EM, battery, ICE, HP and HM) to achieve optimal operational performance. The overall proposed strategy is compared with alternative frameworks existing in the literature based on Intelligent Hierarchical Hybrid Controller Strategy (IHHCS) [8] in order to demonstrate the advantages of the new proposed

[1] http://www.businova.com

methodology (cf. section IV). The results of this paper support that the proposed strategy is capable of: (i) being applied to various types of hybrid vehicle; (ii) increasing global vehicle efficiency; (iii) being implemented in real-time; (iv) keeping SOC within the range which promotes battery longevity compared to IHHCS [8].
The paper is organized as follows. The overall HHEV's description and modeling is given in section II. In section III, the proposed controller structure is developed. Simulation results and comparative analysis using IPG automotive TruckMaker simulator are presented in section IV. Finally, the conclusions and future prospects are presented in section V.

II. MODELING OF THE HYBRID BUS

The aim of this section is to illustrate the architecture and the mathematical model of the studied system, i.e., BUSINOVA hybrid bus, developed by SAFRA company.

A. Hybrid Bus Powertrain Architecture

The model of the studied hybrid bus is based on a series-parallel power-split hybrid architecture [11]. A simple block diagram of the power flows in the bus is shown in Figure 1. The EM and HM are both directly connected to the

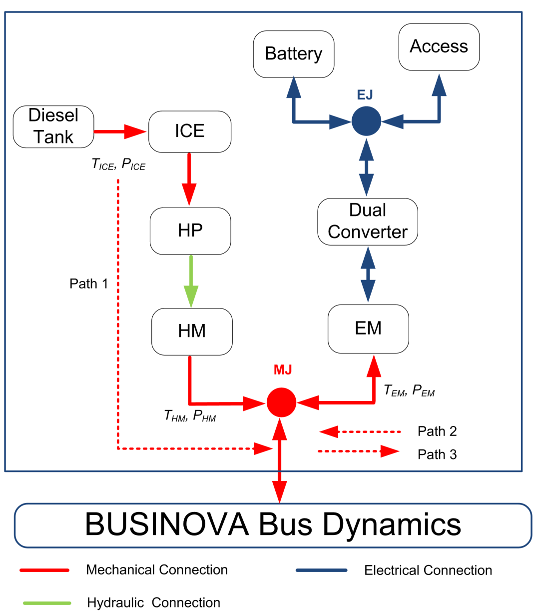

Fig. 1. Block diagram of the powertrain power flows.

transmission and can ensure simultaneously or independently the traction of the bus. On the other hand, the ICE is coupled to a HP for driving the HM, and therefore allowing the ICE load shifting.

B. Dynamical Model

This part is dedicated to the dynamical equations describing the bus (cf. Figure 2). It is supposed that Center of Mass (CoM) of the bus is in its geometric center. The bus is moving along x-axis in the positive direction, The forces acting on a BUS (of mass m) which travels with a Linear acceleration $\vec{a}$ is expressed by the second law of Newton

$$\sum_i \vec{F_i} = m\vec{a} \tag{1}$$

With $\vec{F_i}$ corresponds to the different forces acting on the BUS (cf. Figure 2): Force of gravity $\vec{F_g}$, traction force $\vec{F_t}$, rolling resistance force $\vec{F_{rr}}$ and aerodynamic force $\vec{F_{ad}}$, (1) can be rewritten in the following form:

$$(M + M_{eq})a = F_t - F_{rr} - F_{ad} - F_g sin(\theta) \tag{2}$$

wher a is the bus acceleration, F_t is the traction force, F_{rr} is the rolling resistance, F_{ad} is the aerodynamic force, M is the bus weight, and M_{eq} is the equivalent mass of rotating parts. The traction force F_t is the linked to the torque produced by the output powertrain (T_{pt}) is the via gear ratio (i_g), powertrain efficiency (η_{pt}). Expanding the dynamical equation (2), the following relation is obtained [12]:

$$a = \frac{dv}{dt} = \frac{1}{M + M_{eq}} \frac{i_g \eta_{pt} T_{pt}}{r} - \mu_{rr} F_N sign(v) - \frac{1}{2}\rho A C_d (v + v_{wind})^2 - Mg\sin(\theta) - \frac{T_{brake}}{r} \tag{3}$$

where μ_{rr} is the rolling resistance coefficient, $F_N = Mgcos(\theta)$ is the normal force, g is thegravity acceleration, θ is the slope angle, ρ is the air density, A is the frontal area of the bus, C_d is the drag coefficient, v_{wind} is the wind speed and T_{brake} is the brake torque provided by the bus mechanical brake system. The associated wheel power (P_{hev}) for the vehicle is given by $P_{hev} = M\frac{dv}{dt} + F_t + \sin(\theta)$.

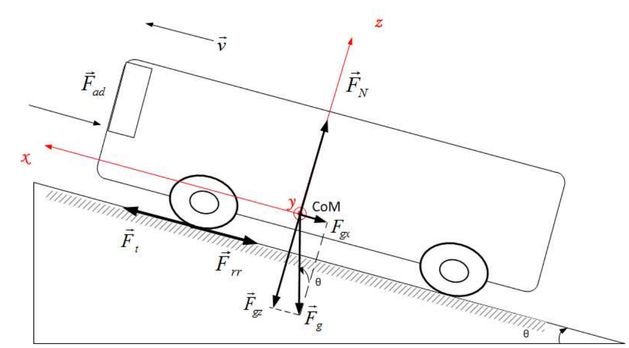

Fig. 2. Forces acting on the bus.

C. Simplified Powertrain Model

In this section, we will present the HM model through ICE, the EM and battery models as the following.

1) Hydraulic Motor Coupled to Internal Combustion Engine: In this paper, ICE torque versus ICE speed is directly derived from the ICE fuel consumption model. The fuel flow rate $\dot{m}_f$ of the ICE is defined by, $\dot{m}_f = f_{ICE}(T_{ICE}, \omega_{ICE})$, where ω_{ICE}, T_{ICE} are respectively rotational speed and torque of the ICE. The function f_{ICE} is obtained from the ICE bench tests. The power consumed by the ICE (P_{ICE}) is given by P_{ICE}=$\dot{m}_f(T_{ICE}, \omega_{ICE})Q$, (i.e., P_{ICE} is the instantaneous power of the fuel expressed in terms of $\dot{m}_f$ and the lower heating value of the fuel (Q = 43MJ/kg)).

2) Electric Motor: The powers required for the EM were calculated from the known EM torque and speed by using EM efficiency curve. The output torque T_{EM} of the EM is defined by, $T_{EM} = f_{EM}(P_{EM}, \omega_{EM})$, where P_{EM} is the EM input power, ω_{EM} is the EM current speed. The function f_{EM} is also obtained from the EM bench test. Taking into account the efficiency of the electrical drive system including the efficiency of the final drive, the power on the HHEV bus (P_B) can be calculated as follows:

$$P_B = \frac{P_{hev}}{\eta_e} \tag{4}$$

where η_e is the efficiency of the electrical drive system.

3) Battery Model and Efficiency: In this paper a practical electrical circuit model based on [13] for lithium-ion batteries is proposed. The total battery power can be calculated as follows:

$$P_{bat} = P_B + P_{ICE} = \frac{P_{hev}}{\eta_e} + P_{ICE} \tag{5}$$

With these modelling assumptions the battery state dynamics is described by

$$SOC = SOC_i - \frac{1}{3600C_n}\int_0^t \frac{P_{bat}}{V_{bat}} dt \tag{6}$$

Where V_{bat} is the battery voltage, SOC_i is the battery SOC initial value and C_n is the nominal capacity in Ampere-hours (Ah) which defines the manufacturers rated battery capacity.

III. PROPOSED OPTIMAL ENERGY MANAGEMENT STRATEGY BASED ON THE PREDICTION OF BUS'S FUTURE STATES

After the proposition of an accurate model for BUSINOVA bus, it is proposed in what follows a flexible and reliable strategy to minimize the bus total energy consumption (though the maximization of the global vehicle efficiency) in order to ensure the mileage of continuation of journey.Therefore, in this section, an intelligent energy management is proposed which is capable of meeting various objectives including optimized power flow management, maintaining high operational efficiency of the ICE, and balancing EM and battery charge to maximize the global vehicle efficiency. A possible interaction of the proposed management in the vehicle control environment is proposed in Figure 3. The control architecture is based upon three different levels. Extended Driver Interpretation is devoted to the interpretation of driver demands. It analyzes signals coming from driver actuators such as throttle pedal, gear shift lever, zero emission vehicle button (i.e, which forces a purely electric drive), etc. and the vehicle environment (e.g., road slope, traffic jam, etc.). With this information, it calculates the required torque at the wheel (T_{demand}) and drivability constraints to ensure a smooth drive. The third level has been developed by ANFIS (Adaptive Neuro Fuzzy Inference System) to predict SOC of the battery for the whole Driving ($\hat{SOC}_{pred}$) and the power consumption of the vehicle over a given prediction time horizon ($\hat{P}_{hev}$). In addition, this level uses according to the map optimal efficiency of EM and ICE, and its state variables measurements, EM and ICE optimal efficiencies are predicted ($\hat{\eta}_{EM,opt}$, $\hat{\eta}_{ICE,opt}$) (cf. section III.A). In the second level, an energy management strategy has been developed for power splitting which decides the optimal combination of power sharing between different energy sources to maximize overall vehicle efficiency (cf. section III.B). The first level describes a low level robust fuzzy control to track the set points of EM and HM via the ICE generated at the second level (cf. section III.C).

A. Prediction Horizon Strategy based on ANFIS (Level 3)

In the predictive level the optimal control problem is solved based on the trip prediction. A good prediction of road conditions like road slope, ambient temperature and wind speed is required in most hybrid system applications, especially in the energy management. In this paper, an ANFIS model [8] is used to estimate the driving cycle conditions. The idea consists of using the intelligent transportation data (Global Positioning System (GPS), radar,...) with local measurement data for short-term and long term prediction of ambient conditions. Based on the analysis of the locally collected data, the power potentials noted by battery SOC ($\hat{SOC}_{pred}$), power consumption of the vehicle over a given prediction time horizon ($\hat{P}_{hev}$) and EM and ICE optimal efficiencies ($\hat{\eta}_{EM,opt}$, $\hat{\eta}_{ICE,opt}$) are obtained using respectively, Battery, EM, ICE and vehicle dynamic models.in this paper will make the focus on optimal Energy management given in Level 2 (cf. next subsection).

B. Optimal Energy Management Strategy (Level 2)

Once level 3 has predicted the SOC of the battery for the whole driving day, the power consumption by vehicle over a given prediction time horizon and the optimal efficiency for EM and ICE, this level of control manages and optimizes the power distribution between the two different sources based on new proposed formulation. This section presents in details the proposed algorithm in order to optimize power distribution between EM or/and HM via ICE based on the following Theorem.

Theorem: Based on the predicted battery SOC, the power consumption of the vehicle for the whole driving day and the current optimal efficiency of the ICE and EM, the torque split between the ICE and the EM is obtained as following.

$$\begin{aligned} T_{EM,sp} = (&\frac{\hat{\eta}_{EM,opt}}{\alpha\hat{\eta}_{ICE,opt} + \hat{\eta}_{EM,opt}})T_{demand} \\ &- \frac{\hat{\eta}_{EM,opt}\hat{\eta}_{ICE,opt}}{\alpha\hat{\eta}_{ICE,opt} + \hat{\eta}_{EM,opt}}\left(\frac{\alpha\hat{P}_{hev}}{\beta\omega}\right)^{1/2} \end{aligned} \tag{7}$$

$$T_{ICE,sp} = T_{demand} - T_{EM,sp} \tag{8}$$

where, $\hat{\eta}_{EM,opt}$ is current optimal predictive efficiency for EM, $\hat{\eta}_{ICE,opt}$ is current optimal predictive efficiency for ICE, α is the weight which depends on the current SOC value and the predicted SOC value at the end of the day, $\hat{P}_{hev}$ is

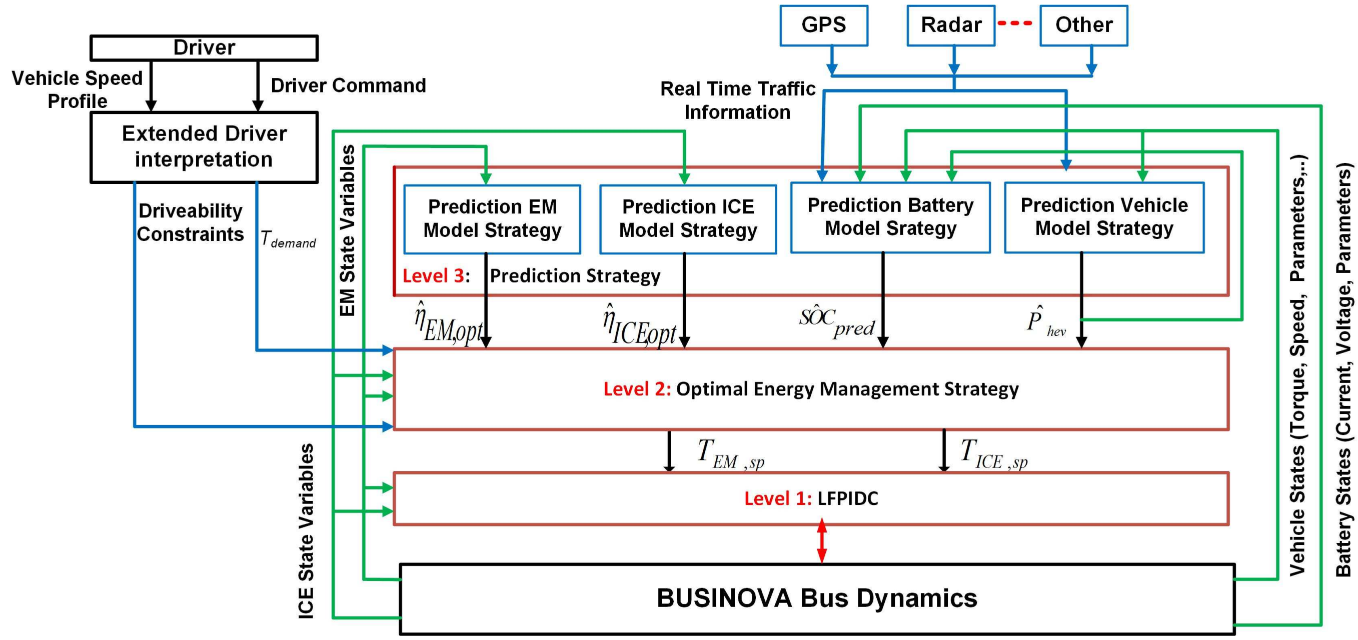

Fig. 3. Developed intelligent energy management strategy for BUSINOVA bus.

the current predictive power of the vehicle, T_{demand} (Torque demand) which is required to drive the vehicle and is defined by the global torque set point, ω is the speed of the ICE or EM (since in the design of the studied bus requires that ω_{EM} $=\omega_{ICE}=\omega$),β is positive small value.

Proof. The proof can be given as the following. The overall optimization algorithm consists to maximize the efficiency of the hybrid vehicle which is given by,

$$\eta_{hev} = \frac{P_{hev}}{P_{ICE} + P_{EM}} \tag{9}$$

The consumed EM and ICE power are given by,

$$P_{EM} = \alpha P_{elec} = \mathrm{I}_{bat} V_{bat} \quad ; \quad P_{ICE} = Q\dot{m}_f \tag{10}$$

where weight calculation factor (α) is defined by

$\alpha = k\tanh(dSOC + b) - k\tanh(d\hat{SOC}_{pred} + b)$, with the requirements ends up with the following equations: $d = \frac{-\pi}{0.5236}(SOC_{max} - SOC_{min})$, $b = \frac{-\pi}{0.5236} - dSOC_{min}$, $k_p = \frac{k_{pMax} - k_{pMin}}{15} abs(\hat{SOC}_{pred} - SOC) + k_{pMin}$, $k = \frac{k_p}{d} cos(d\hat{SOC}_{pred} + b)^2$, where k_p is the gain of the controller which changes between k_{pMin} and k_{pMax}. If the efficiency of the EM and ICE are given by

$$\eta_{EM} = \frac{T_{EM}\omega_{EM}}{\mathrm{I}_{bat}V_{bat}} \quad ; \quad \eta_{ICE} = \frac{T_{ICE}\omega_{ICE}}{Q\dot{m}_f} \tag{11}$$

From (9), (10) and (11), the overall efficiency of the hybrid vehicle is given by, $\eta_{hev} = \frac{P_{hev}}{\frac{T_{ICE}\omega_{ICE}}{\eta_{ICE}} + \alpha\frac{T_{EM}\omega_{EM}}{\eta_{EM}}}$.

Considering that,

$$\eta_{ICE} = \hat{\eta}_{ICE,opt} = C_1 \quad ; \quad \eta_{EM} = \hat{\eta}_{EM,opt} = C_2 \tag{12}$$

To calculate the optimal torque, we consider that, $T_{ICE,sp} = f(\hat{\eta}_{ICE,opt})$ and $T_{EM,sp} = f(\hat{\eta}_{EM,opt})$, therefore assume that,

$$T_{ICE,sp} = XC_1 \quad ; \quad T_{EM,sp} = YC_2 \tag{13}$$

The objective is thus to define how to find X and Y to maximize (optimization) the overall efficiency of the by studied HHEV. If $T_{demand} = T_{ICE} + T_{EM}$, then from (12) and (13) we have,

$$T_{demand} = XC_1 + YC_2 \tag{14}$$

$\hat{P}_{hev}$=P_{hev}, $Z = \eta_{hev}$ and $W = \frac{\hat{P}_{hev}}{\omega}$, then we have,

$$Z = \frac{W}{\frac{XC_1}{C_1} + \alpha\frac{YC_2}{C_2}} = \frac{W}{X + \alpha Y} \tag{15}$$

To find X and Y which maximize (optimization) the overall efficiency of the studied HHEV, based on the derivatives of a function Z and some calculus theorems, is developed in order to find an analytical solution to this problem.

$$\frac{\partial Z}{\partial Y} = 0 \cong \beta \quad ; \quad \frac{\partial Z}{\partial X} = 0 \cong \beta \tag{16}$$

From (14), (15) and (16), we have,

$$Y = \left(\frac{1}{\alpha\hat{\eta}_{ICE,opt} + \hat{\eta}_{EM,opt}}\right)T_{demand} - \frac{\hat{\eta}_{ICE,opt}}{\alpha\hat{\eta}_{ICE,opt} + \hat{\eta}_{EM,opt}}\left(\frac{\alpha\hat{P}_{hev}}{\beta\omega}\right)^{1/2} \tag{17}$$

in the same manner we can obtain X.

Based on equations (12) to (14) and (17), the set point torque for the ICE and EM which are given in (13) can be rewritten as (7) and (8) which are given in the Theorem.

From the derived theorem, it can be seen that a novel hybrid algorithm was proposed to create an optimal power distribution between EM or/and HM via ICE, which take the effect of the vehicle dynamics in consideration, since the strategy is based on the global vehicle efficiency and the required torque.

C. Local Fuzzy Tuning Proportional-Integral-Derivative Controllers (Level1: LFPIDC)

The objective at this level is to regulate the set points of EM and HM via ICE, to give a good control tracking performance. As mentioned before, level 2 (cf. section III.B) allows us manage optimally the power distribution between the different sources during operation mode, while sending out reference torque signals to each individual hybrid vehicle subsystem (e.g., HM via ICE, EM, battery, etc.), level 1 with LFPIDC ensures that this reference torque signals are tracked as accurate as possible. In addition, the low level control strategy based on LFPIDC has the ability to keep the hybrid vehicle system states stable even in the presence of uncertainties. In this level, it is proposed fuzzy logic tuning PID controller based on [14] for the EM and HM via ICE.

IV. SIMULATION RESULTS AND DISCUSSION

To verify the BUSINOVA bus model and the control performance of the proposed overall control and optimal energy management strategy, the effectiveness of the proposed overall control architecture is highlighted and a comparison with IHHCS [8] is discussed. The desired and the actual bus speed profile is shown in Figure 4 (left). Figure 4 (right) shows the driver torque demand and the actual wheel torque for the proposed energy management strategy and IHHCS [8].

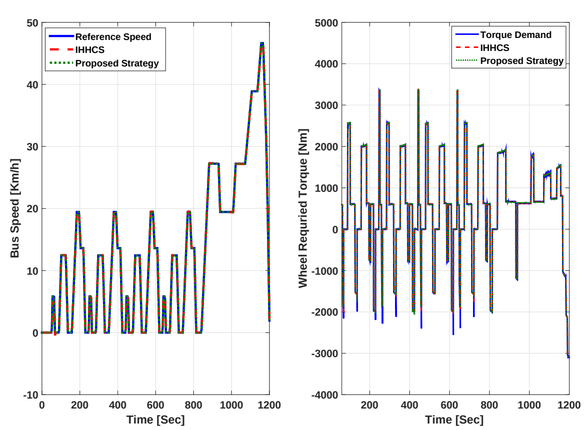

Fig. 4. Output vehicle speed [Km/h] (left) and actual wheel required torque [Nm] (right) for proposed energy management strategy and IHHCS [8].

Figure 5 (left) depicts the progress of SOC and Figure 5 (right) shows the total energy consumed [KJ] using proposed strategy and IHHCS [8].

From Figures 4 and 5, simulation results indicate that the proposed energy management control method can achieve increased energy efficiency and minimize the total energy

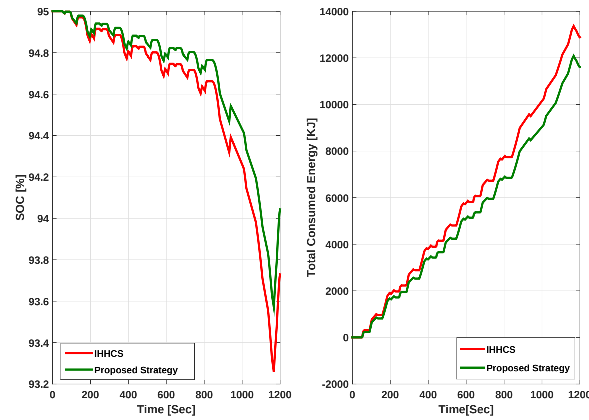

Fig. 5. SOC profiles (left) and total energy consumed [KJ] (right) for proposed energy management strategy and IHHCS [8].

consumption (summation of electric energy and fuel energy) compared to IHHCS [8]. These enhancement is mainly due to the fact that the new proposed strategy allows to make operate ICE and EM always near their optimal current efficiency with a good balance between these two degrees of freedom.

V. Conclusion and Prospects

This paper discusses two important aspects of the control and optimization of hybrid hydraulic-electric vehicle's power management. The first part of this work is dedicated to the development and validation of a dynamic HHEVs model using MATLAB/TruckMaker. The obtained results given in section IV confirm the fidelity of the model under a variety of operating conditions. The second part of this paper focuses on power management and optimization development. The value of the proposed methods are demonstrated under various driving schedules through comparison with another method. The results confirm that, using the proposed approach: (i) an accurate and reliable model of the BUSINOVA bus is realized by TruckMaker software; (ii) the proposed strategy effectively splits "with efficient way" the torque between EM and HM via ICE; (iii) global vehicle efficiency is improved as well as the total average distance achieved between refueling; (iv) EM and ICE are operated near its optimal range. Hence, this paper provides a novel model and novel approach for an advanced power management system of hybrid vehicles. It is planned in the near future to implement the overall proposed control strategy on the actual BUSINOVA platform.

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