Abstract- The simulation of a Hybrid Electric Vehicle (HEV) using the Energetic Macroscopic Representation (EMR) is suggested in this paper. Indeed, the EMR organizes systems as interconnected sub-systems, improving modularity and flexibility. Firstly, primary and secondary sources’ dynamical models are developed using the EMR. Batteries, Ultracapacitors (UCs), rheostat, diesel driven generator set and the HEV load are concerned in this kind of application. Secondly, the implementation of the local control or the Maximum Control Structure (MCS) of each element is realized. Finally, two Energy Management Strategies (EMSs) are implemented using the software Matlab-Simulink®.

I. INTRODUCTION

The HEV concept is born in 1905 when the American engineer H. Piper filed for a patent on a hybrid vehicle. An electric motor was used to augment a gasoline engine. However, three years later, Internal Combustion Engines (ICEs) became powerful enough to achieve desired performances. Even if the 1970s’ oil crisis marked a timid revival of the construction of several experimental HEVs, interests were almost nonexistent until the 1990s. In 1997, almost a century after the hybrid was first conceived, the hybrid electric light vehicles have been commercialized by introducing the Toyota Prius to the market [1]. Because of the environmental, ecological (reduction of CO₂ emissions) and economical issues (drying up of petroleum reserves), the Toyota Prius success encourages the researchers to consider hybrid applications in more heavy-duty vehicles. Indeed, the hybridization of buses [2], trucks [3], or locomotives [4] prove that energy could be used without important negative environmental impact. The studied system is a Hybrid Electric Locomotive (HEL). The existing shunting activities are usually performed by locomotives equipped with a noisy diesel engine and not stopping when the locomotive is in idle mode. An advanced proposed solution is to downsize the diesel electric propulsion and synchronized it with a battery/ultra-capacitors propulsion system, more respectful to the environment. A first study available in [5] presents the studied locomotive structure and is reminded on figure 1. It also describes the sizing of the secondary power sources of the locomotive based on [6]. The next step of the projects’ aim is to implement the EMR of the system with its Maximum/Practical Control Structure (M/PCS) using Matlab-Simulink®. In the case of a multi-physical system like the studied HEL, graphical descriptions (bond graphs [7], power oriented graphs [8], or causal ordering graphs [9]) are well suited for the modeling. The EMR can be specifically used for the modeling and the control of multi-physical systems too. In respecting the principles of physical causality and interaction, the system is also decomposed into interconnected elements.

In this paper, the first part is dedicated to the study and the modeling of the HEL’s power sub-systems using the EMR. The second part aims at presenting two energy management strategies (EMSs). Indeed, an energy management strategy must be designed to control the power flows between the energy sources because of their influences on vehicle performances and fuel economy [10]. The different approaches used can be classified in two categories presented in [11] and [12]:

- Optimization-based strategies (optimal control, dynamic programming) requiring a knowledge of the power profile and used off-line [13];
- Rules-based management strategies used on-line (deterministic rules, artificial intelligence) [14].

Thus, this second part of the paper is organized as follows. First, a frequency EMS is presented to confirm the good implementation of the sub-systems’ models. Then, an EMS using a Fuzzy Logic Controller (FLC) (second category) is described.

II. DIESEL DRIVEN GENERATOR SET MODELING

This model includes dynamics phenomena (mechanical and fluidic ones). It also proposes speed and torque control of the mechanical shaft of the engine and the Lower Heating Value
(LHV) of a substance is used to characterize the type of fuel injected into the cylinders. The modeling of the alternator (a salient pole synchronous machine) is mainly based on the work of [15] and [16]. Both of the systems’ (engine and alternator) EMR, M/PCS, equations and simulation results have already been presented in details in [17]. Figure 2 presents the EMR and the PCS of the diesel driven generator set.

III. ULTRA-CAPACITORS MODELING

The adopted UCs’ cell model is based on [18]. The use of a simple Resistive Capacitive (RC) equivalent circuit is insufficient to characterize the behavior of a double layer capacitor for power applications. Thus, an equivalent circuit consisting in two RC branches is used (figure 3 – equation 1).

\[
\begin{align*}
\frac{r_1(s)}{i_1(s)} &= \frac{v_t(s)}{R_d + \frac{1}{C_d s}} \\
V_t(s) &= R_d i_1(s) + \frac{i_1(s)}{(C_{i0} + C_{i1} V_t(s)) s}
\end{align*}
\]

(1)

The UCs’ pack model takes into account the previous presented model of an UC’s single cell. The power electronics necessary to link it to the central DC bus is made up of a smoothing filter and a DC chopper. The smoothing filter is a RL circuit and realizes the smooth of the direct current wave shape (equation 2).

\[
V_{uc}(t) - V_{h-uc}(t) = R_{uc} h_{uc}(t) + L_{uc} \frac{dh_{uc}(t)}{dt}
\]

(2)

with, \( R_{uc} \) the resistance and \( L_{uc} \) the inductance of the filter. The DC chopper is considered as its mean value model (equation 3).

\[
\begin{align*}
\begin{cases}
I_{uc} &= \alpha_{uc} I_{h-uc} \\
V_{h-uc} &= \alpha_{uc} V_{bus}
\end{cases}
\end{align*}
\]

(3)

The MCS aims at controlling the current applied to the UCs’ packs \( (I_{uc}) \). Thus, it is made up of two mono-physical inverters and one PI controller. The UCs’ SOC is an important variable which must be taken into account in EMSs. It is not physically measurable but its estimation is possible (equation 4).

\[
SOC_{uc_{eest}} = \frac{V_{uc_{meas}}}{V_0}
\]

(4)

EMR and M/PCS of a pack of UCs are represented on figure 4.

IV. BATTERIES MODELING

The considered batteries are Nickel Cadmium (NiCd) batteries. Electrodes are made up of Nickel oxide hydroxide and metallic cadmium. Based on [19] and [20], an improved and easy-to-use battery cell dynamic model is simulated. The model takes into account charging/discharging dynamics and hysteresis phenomena. The discharging behavior is represented by the equation 5 and the charging behavior by the equation 6.

\[
\begin{align*}
V_{batt} &= E_0 - R_i - K_i \frac{Q}{Q - R_i i} - \cdots \\
&= K_2 \frac{Q}{Q - R_i i} + Ae^{-B_i t}
\end{align*}
\]

(5)
\[ V_{\text{batt}} = E_0 - Ri - K_1 \frac{Q}{|t|} - 0.1Qi^* - \ldots - K_2 \frac{Q}{|t|} - 0.1Qi + Ae^{-B|t|} \] (6)

with \( V_{\text{batt}} \) the voltage (V), \( E_0 \) the constant voltage (V), \( K_2 \) the polarisation constant (V/Ah), \( K_1 \) the polarization resistance (V/A), \( Q \) the capacity (Ah), \( i_t \) the actual charge (Ah), \( R \) the internal resistance, \( i \) the current (A), \( i^* \) the filtered current (A). The exponential term is made up of two constants relative to the exponential zone amplitude \( A \) (V) and to the exponential zone time constant inverse \( B \) (Ah\(^{-1}\)) determined using the discharge curve of the battery.

The associated power electronics are the same as the pack of UCs ones. Thus, representations and controls are equally the same like ultra-capacitors’ ones (figure 4). However, the estimation of the batteries’ SOC is performed thanks to equation 7.

\[ \text{SOC}(t) = \text{SOC}_0 - \frac{\int i(t) dt}{Q} \] (7)

V. ARCHITECTURE OF THE SYSTEM

The central DC bus links and imposes a common voltage (\( V_{\text{bus}} \) – equations 8 and 9) to the primary/secondary sources, the load and the rheostat (figure 5). The rheostat is used like a security. The recovered breaking energy is stored into the batteries and the ultra-capacitors. If those elements are overcharged and if the electrical network is not able to recover this energy, it is dissipated in the rheostat.

VI. ENERGY MANAGEMENT STRATEGIES OF THE HEL

The first part of the article presented the EMR and M/PCS models of the whole HEL. This second part concerns the establishment of the EMS of the HEL. It consists in determining currents references of the diesel driven generator set, the batteries and the UCs packs to insure the considered power mission and the control of the bus voltage. Thus, two different EMSs are presented. Experimental results (powers - voltages) are normalized on figures (pu) for confidential reasons.
A. EMS based on a frequency approach of the sources

To validate the good implementation of the previous presented models, a first EMS, based on a frequency approach [21], is used. The mission power (figure 7) is filtered thanks to a low pass filter. From this filter, low and high frequencies of the power mission are obtained. High frequencies define the UCs power request (or reference) and low frequencies, batteries and diesel driven generator set powers requests. Batteries and UCs’ States Of Charges (SOCs) are respectively limited between 70%-90% (figure 12) and 50%-100% (figure 11). It avoids over-charging and deep discharging for batteries and it corresponds to the nominal voltage and the half of the nominal voltage of the UCs. This first EMS (models validation purpose) does not take into account a possible re-charge of the batteries. Thus, when batteries are totally discharged (figure 10), elements are no more solicited and the diesel driven generator set (figure 8) completes the power demand (figure 7).

Figure 13 also shows that the bus voltage control remains stable. Other simulation results have also proven that in the case of degraded mode (batteries and/or UCs totally discharged), the presented PCS insures the control of the bus voltage using only the diesel driven generator set.

B. EMS based on Type-1 Fuzzy Logic

Fuzzy logic aims at translating the human behavior or approach into a language understandable by computers. Fuzzy Logic Controllers (FLCs) find application in many complex systems which controls are difficult to implement. Considering the studied application of the paper (HEL), an EMS based on fuzzy logic permits managing the different on-board sources without prior knowledge of the driving cycle. The implemented (FLC) has the same structure (figure 14) as in [22]. The first input is the error between the batteries’ SOC and their dynamic reference (equations 10 and 11).

\[ e^{\text{SOC}_{\text{batt}}} = \frac{1}{\text{DOD}_{\text{batt}}} \times (\text{SOC}_{\text{batt ref}} - \text{SOC}_{\text{batt est}}) \] (10)

\[ \text{SOC}_{\text{batt ref}} = \text{SOC}_{\text{batt max}} - \frac{V_{\text{veh}}}{V_{\text{veh max}}} \cdots \left( \text{SOC}_{\text{batt max}} - \text{SOC}_{\text{batt min}} \right) \] (11)

with DOD_{batt} the Depth Of Discharge of the batteries, SOC_{batt ref} the batteries’ SOC reference according to the speed of the vehicle (V_{veh}) and SOC_{batt est} the batteries’ SOC estimation.

The second input is the difference between the reference load power and the diesel driven generator set power (equation 12).

\[ dP = \frac{P_{\text{mission}} - P_{\text{ICE meas}}}{P_{\text{mission max}}} \] (12)

The output is the relative power change of the diesel driven generator set (dP_{ICE}). All inputs and output are normalized between [-1;+1] and based on three membership functions (MFs) (N – negative, Z – zero and P - positive). The considered rule base is given in table 1.
Fig. 15. MFs of the input 1.  
Fig. 16. MFs of the input 2.  

Fig. 17. MFs of the output. 

Fig. 18. Fuzzy surface of the controller.  

Fig. 19. Bus voltage according to time using a FLC. 

Fig. 20. Power delivered by the diesel driven generator set according to time using a FLC. 

Fig. 21. Power delivered by the UCs according to time using a FLC. 

Fig. 22. Power delivered by the batteries according to time using a FLC. 

Fig. 23. Batteries’ SOC according to time using a FLC. 

Fig. 24. UCs’ SOC according to time using a FLC. 

Table I  

<table>
<thead>
<tr>
<th>dP</th>
<th>e*SOCbat</th>
<th>N</th>
<th>Z</th>
<th>P</th>
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<td>N</td>
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Example: IF dP is N AND e*SOCbat is N THEN dP_{ICE} is N. 

IF the power provided by the diesel driven generator set is higher than the power required by the mission AND if batteries have to be discharged THEN the power provided by the diesel driven generator set is decreasing.

Figures 15, 16 and 17 present the considered MFs (2 trapezes - 1 triangle for inputs and intervals for the output). Figure 18 is the fuzzy surface of the controller. MFs parameters are obtained using a genetic algorithm which fitness function aims at minimizing the use of the diesel driven generator set.

The same driving cycle represented on figure 7 is used to obtain the results of figures 19 to 24. As a result, the bus voltage remains controlled (figure 19). According to the batteries and the diesel driven generator set behaviors (figures 20 and 22), the FLC permits now recharging batteries.
(negative powers) thanks to the primary source. Batteries’ SOC is still maintained between 70% and 90% (figure 23). It is interesting to notice that the power peaks of the diesel driven generator set (figure 20) are due to a “security” implemented in the EMS. Indeed, all sources remain to be controllable. Thus, all sources participate to the bus voltage control. In the case where batteries and UCs have reached their minimum SOC’s level, they cannot provide power anymore. This case happens at time 2h of the simulation (SOC_{bat} = 70% and SOC_{uc} = 50%). At this time, the diesel driven generator set has to provide the necessary power required by the mission to insure the bus stability.

VII. CONCLUSION

In this paper, the EMR of the studied HEL has been presented. This graphical tool permits the modelling of various systems with multi-physical domains. Using this representation, local controls or MCS have easily been deduced and the PCS has permitted to highlight the necessary sensors to be used. Simulations have lead to the understanding of the dynamical behaviors of the systems like the diesel driven generator set. In the second part of the paper, two different energy management strategies have been successfully implemented. The EMS based on the frequency filtering of the power mission has proven the good implementation of the HEL model. The second developed EMS based on fuzzy logic permits imposing power references to each source without having a prior knowledge of the driving cycle and according to the human knowledge. Thus, it is possible to recharge batteries using the diesel driven generator set. That “intelligent” EMS is the first step toward a deeper study in the development of the fuzzy logic EMS. Indeed, according to the good results obtained in [22], the work will be focused on the optimization of membership functions’ parameters of the Interval Type-2 Fuzzy Logic Controller using genetic algorithms. As proposed in [23] and to better model uncertainties link to the system, General Type-2 Fuzzy Logic will also be used in the EMS.

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