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Dynamic modelling of a series Hybrid electrical vehicle

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***Abstract*— This paper presents a dynamic representation of a series hybrid electric vehicle. The mathematical models of the overall essential components in the car are elaborated. The AC/DC and DC/AC converters, the used electrical and thermal motors and the battery are these constituents. Basing on the vector control method and on a standard power management control method the overall system is built on the Matlab Simulink software. The presented results validate the performance of system control.**
***Keywords*: series hybrid vehicle, PMSM, GMSM, rectifier, inverter, DC/DC converter, battery.**

I. INTRODUCTION

Modern vehicles with internal combustion engine (ICE) are characterized by their comfort, high performance and suitable prices. They present high consumption for low efficiency. In fact, the ICE combustion reaction convert only 30% of the energy produced into mechanical power and the 70% of the energy is lost [1]. However the main problem is related to the ICE that liberates exhaust gases as carbon dioxide (CO_2), lower nitrogen oxide, hydrocarbon, carbon monoxide (CO) and soot [1]. Therefore, air pollution is the essential problem related to these vehicles types and consequently electrical vehicles and hybrid electrical vehicle will be most used in order to solve the problem of pollution and consumption.

Electricals vehicles (EV) are a perfect solution which solves the problem of energy crisis and global warming. Their system of propulsion is an electric motor which characterized by a high torque factor and a large speed running zones. However its control method can be complex if the used motor type is the induction machine. The energy sources for this type of car are essentially the Batteries, that provide energy storage and they supply energy to the propulsion system and auxiliary load such as light, radio... This type of cars is environment friendly but they have some limitations such as high prices, short driving range and long charging time.

Two essential electrical vehicles models are presented in the world, the total electrical vehicles and the hybrid electrical vehicles. However, the first types presents a several problems related to the autonomy and prices, therefore the hybrid model is the most used.

Hybrid electrical vehicle (HEV) is developed to overcome the limitation of ordinary cars and electrical vehicle. A conventional internal combustion engine system is combined with an electric propulsion system. The electric motor is used to achieve either fuel economy and atmosphere protection. The HEV are more performed in power conservation than the conventional vehicle. In fact, they use improved technologies such as regenerative brakes which convert the power of the vehicle's kinetic energy into electric power to charge batteries. Plug in hybrid electrical vehicle (PHEV) are a variety of HEV that have a system of recharge. They combine the characteristic of HEV and EV.

The power trains of hybrid vehicle are more complex than the ICE vehicle, therefore we try to present in this work the overall system as different blocs and we will arrange and couple them to put the final system architecture.

This paper heads for the simulation of series hybrid electric vehicle. In section II, a global presentation of hybrid cars compositions and architectures is provided. HEV series components are modeled in section III. In section IV, control strategy used for each component is explained. Simulation results are regrouped and analyzed in section V.

II. THE ESSENTIALS ELEMENTS IN THE SERIES HEV

The series VEH is a vehicle with only electric propulsion system. In figure 1, a series drive train is shown.

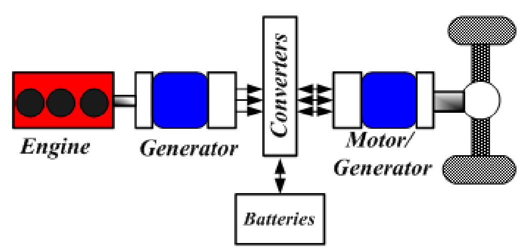

Figure 1: Series power train

The (ICE) provides mechanical energy to the generator which converts this energy to electric power. Battery which is a bidirectional energy source is connected to the power bus throw an electronic converter. Many battery technologies are used in the hybrid cars such as Lead acid, Nickel metal and

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lithium-ion. Li-ion batteries are characterized by careful charging cycle and high energy density, therefore, this model is preferred in the hybrid technology [2]. In other hand the motor in this structure is a bidirectional energy converter, it can be controlled as a motor when it propels the vehicle and as a generator in the braking phase.

There is a several type of electric machine that can be used in hybrid vehicle such as PMSM, induction motor (IM), switching reluctance motor (SRM) and DC motor. The choice of the motor depend on cost, mass, volume efficiency and maintenance. Refers to many works, the PMSM is the most adapted [4].

The converters in this vehicle are also important and necessary such as the DC/DC converter and the AC/DC converter. In this work the two types are presented, modeled and built.

A. Transmission system

The transmission bloc in the HEV can be modeled by the three cited equations: The traction torque, the angular velocity of the wheels and the velocity of the car, given respectively by equations (1), (2) and (3) [4].

$$\Gamma_t = f_t . r_w \tag{1}$$

$$w_w = \frac{w_m}{G} \tag{2}$$

$$v_{car} = w_w . r_w \tag{3}$$

Where f_t is the traction force, w_m is the shaft angular velocity of the electric machine and r_w is the wheel radius. G is the gear ratio of the differential ; it can be calculated by the following equation [4].

$$G = \frac{n_{s,\max}}{v_{car,\max}} \frac{2\pi}{60} \frac{r_w}{1.1} \tag{4}$$

B. Electric Motor

In this work, the PMSM type is used. Equations (5) and (6) illustrate the dynamic behavior of 3 phase's currents in the d-q frame [5].

$$\frac{di_{dm}}{dt} = (v_{dm} - R_m i_{dm} + w_{rm} L_{qm} i_{qm}) / L_{dm} \tag{5}$$

$$\frac{di_{qm}}{dt} = (v_{qm} - R_m i_{qm} - w_{rm} (L_{dm} i_{dm} + \lambda_f)) / L_{qm} \tag{6}$$

Where i_{dm} and i_{qm} are the d-(direct) and q- (quadrature) axis components of stator current, v_{dm} and v_{qm} are the d- and q-axis components of stator voltage; R_m is the stator resistance, L_{dm} and L_{qm} are the d- and q-axis stator inductances, λ_f is the flux linkage due to the permanent magnets, and w_{rm} is the inverter frequency. The electromagnetic torque produced by the motor is described by equation (7).

$$\Gamma_{em} = \frac{3}{2} p_m (\lambda_f i_{qm} + (L_{dm} - L_{qm}) i_{dm} i_{qm}) \tag{7}$$

" p_m " is the number of pair per phase of stator poles. This torque is applied on the rotor shaft that is connected to the car transmission. The mechanical part of the PMSM model is given by equation (8) [5].

$$\Gamma_{em} = J_s \frac{dw_m}{dt} + B . w_m + \Gamma_c + \Gamma_s \tag{8}$$

In which J_s is the shaft moment of inertia and B is the viscous friction coefficient, Γ_c is the coulomb torque or the friction torque, Γ_s is the shaft torque of electric machine, it is the half of the traction torque. The relation between w_{rm} and w_m is described the following equation:

$$w_{rm} = p_m w_m \tag{9}$$

C. Inverter

The model of the bidirectional inverter used in this work is an average model. It can be expressed in the d-q frame by equation (10) [5].

$$i_{inv} = \frac{1}{\eta_{inv}} \frac{3}{2} (d_{di} i_{dm} + d_{qi} i_{qm}) \tag{10}$$

$$v_{dm} = d_{di} v_{dc} \tag{11}$$

$$v_{qm} = d_{qi} v_{dc} \tag{12}$$

Where i_{inv} is the current drawn by the DC link. d_{di} and d_{qi} are the duty cycle functions in d and q axis respectively.

D. DC/DC converter

This converter is used to boost the battery voltage to v_{dc} of the DC link. The output voltage can be adjusted by the duty cycle α_r as shown at the following equation [6].

$$\frac{v_{out}}{v_{in}} = \frac{1}{1 - \alpha_r} \tag{13}$$

The input voltage v_{in} is the battery voltage; the output voltage v_{out} must be fixed. The step-up DCDC model is modeled by the following system of equations:

$$\begin{cases} v_{in} = L_r \dfrac{di_l}{dt} + (1-u) v_{out} \\ i_l (1-u) = c_r \dfrac{dv_{out}}{dt} + i_{out} \end{cases} \tag{14}$$

Where i_l the inductance is current, i_{out} is the current of the load and U is the pulse with modulation.

E. Battery

The charge model of Li-ion battery can be summarized in the following equation [7].

$$\begin{gathered} v_{bat} = E_0 - R_{bat} i_{bat} - \alpha_{bat} i^* - \beta_{bat} Q + A . e^{(-BQ)} \\ \begin{cases} \alpha_{bat} = K \dfrac{Q_{\max}}{Q - 0.1 Q_{\max}} \\ \beta_{bat} = K \dfrac{Q_{\max}}{Q_{\max} - Q} \end{cases} \end{gathered} \tag{15}$$

The dynamic model of discharge is given by equation (16).

$$v_{bat} = E_0 - R_{bat} i_{bat} - \beta_{bat} (Q + i^*) + A . e^{(-BQ)} \tag{16}$$

$$Q = \int i_{bat} dt \tag{17}$$

Q is the actual battery charge ; it is related to the battery current by equation(17).The battery parameters are the battery capacity $Q_{\max}$, the battery constant voltage E_0 , the polarization constant (or the polarization resistance) K and the internal resistance R_{bat} . A and B are respectively the exponential zone amplitude and time. i^* is the filtered current.

F. PMSG

The permanent magnet synchronous generator transforms the mechanical power to electrical power. The model of stator current of the PMSG is given by equations (18) and (19) [5].
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$$L_{dg}\frac{di_{dg}}{dt} = v_{dg} - R_g i_{dg} + p_g \omega_g L_{qg} i_{qg} \quad (18)$$

$$L_{qg}\frac{di_{qg}}{dt} = v_{qg} - R_g i_{qg} - p_g \omega_g (L_{dg} i_{dg} + \lambda_g) \quad (19)$$

Where i_{dg} and i_{qg} are the d-(direct) and q- (quadrature) axis components of stator current, ω_g is the angular frequency of the induced electromotive force, v_{dg} and v_{qg} are the d- and q-axis Components of stator voltage, R_g is the stator resistance, L_{dg} and L_{qg} are the dq axis stator inductances, λ_g is the rotor permanent magnet flux and p_g is the generator number of pole pairs per phase. The PMSG is mechanical coupled to the ICE by a fixed gear ratio G . The mechanical dynamic of the PMSG is given by the equation (20).

$$\Gamma - G(\Gamma_e + \Gamma_f) = (J_{eng} + G^2 J_g)\frac{d\omega_{rg}}{dt} \quad (20)$$

While Γ is the mechanical torque produced by the ICE, Γ_e is the electromagnetic torque of the PMSG, Γ_f is the friction torque of the generator. J_{eng} and J_g are the moments of inertia of the engine. The rotor speed ω_{rg} is related to the source voltage frequency by the following equation.

$$\omega_g = p_g \omega_{rg} \quad (21)$$

G. Rectifier

Similar to the inverter, Average modeling is considered. Then the mathematical model can be described in the following equation [5].

$$i_{rec} = \frac{3}{2}\eta_{red}(d_{dr} i_{dg} + d_{qr} i_{qg}) \quad (22)$$

The duties cycles d_{dr} and d_{qr} are similar to the model of inverter described previously.

H. Internal combustion engine ICE

ICE provides mechanical power to the generator. The engine model used is a parabolic model as presented in equation (23) [8].

$$\Gamma = \Gamma_{\max} - \frac{P_{\max}}{2\omega_p{}^2(\omega_p - \omega_t)}(\omega - \omega_t)^2 \quad (23)$$

The engine produces mechanical torque Γ at the speed ω . ω_t is the speed at maximum torque. ω_p is the speed at maximum power.

III. Control Strategy Description

Several Regulators are used in this work in order to control this system. The proportional-integrator PI regulator kind is the unique type used.

Firstly, the PMSM is controlled in order to control the vehicle speed. The used control strategy is the vector control.

The PI controller associated the PMSM system has the following form:

$$F_{PI}(s) = \begin{bmatrix} K_d(1 + \frac{1}{sT_{id}}) & 0 \\ 0 & K_q(1 + \frac{1}{sT_{iq}}) \end{bmatrix} \quad (24)$$

Here α is the time constant of the filter used.

$$\begin{cases} Kq = \alpha L_{qm} \\ T_{iq} = \frac{L_{qm}}{R_m} \end{cases} \begin{cases} K_d = \alpha L_{dm} \\ T_{iq} = \frac{L_{dm}}{R_m} \end{cases}$$

In PMSG, the strategy of control used is similar to PMSM. The speed of both synchronous generator and engine is controlled. The i_d current is forced to zero and i_q follows i_{qref} given by the controller of the speed controller. The PI regulator of generator speed makes the speed follow a speed that provides maximum power.

$$v_{dc} = \int (i_{red} + i_h - i_{inv})dt \quad (25)$$

By reference to equation (25), the DC-link voltage v_{dc} depends on the DCDC converter current in both charge and discharge mode. It is regulated by an integrator controller that provides the duty cycle to the set-up converter.

IV. Simulation Results

In this work we have implemented the global model of series HEV with SIMILINK MATLAB platform and we have used for the electric machines, engine and battery models the parameters shown in Table 1, Table 2 and Table 3.

Table 1: Parameters of the electric machines

Parameters	***PMSM***	***PMSG***
Nominal rated power	75Kw	92KVA
Maximum speed	5000RPM	5000RPM
Stator resistance	0.04Ω	0.04Ω
D,Q axis inductance	0.002mH	0.0045mH
Rotor magnetic flux	0.1252Wb	0.2125Wb
Moment of inertia	0.05Kg.m^2	0.05Kg.m^2
Number of pole pairs	6	6

Table 2: Parameters of the internal combustion engine

Parameters	***Values***
Peak power	103Kw
ω at peak power	6300RPM
Peak torque	174 Nm
ω at peak torque	4300 RPM

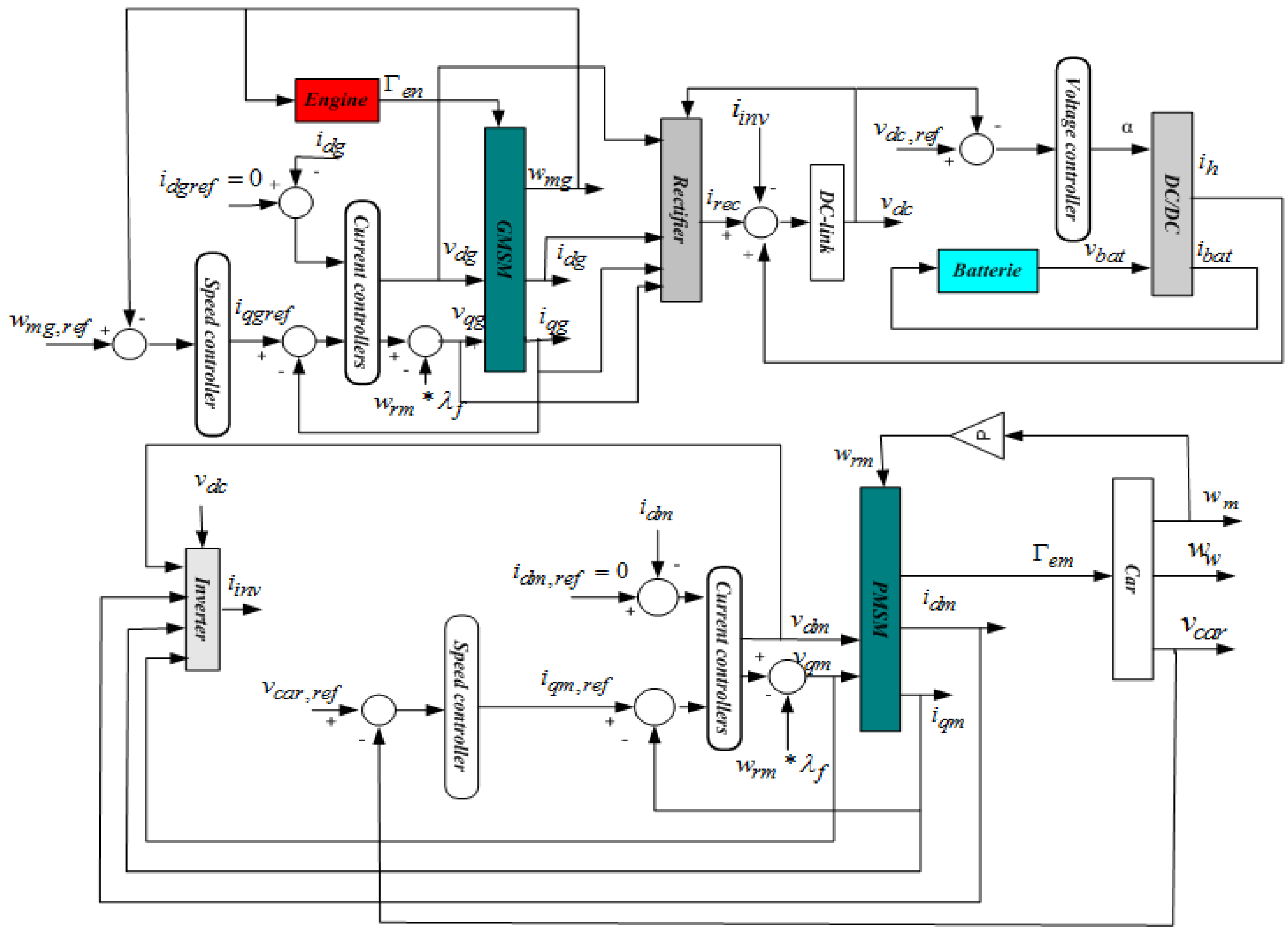

Figure 2: Series hybrid vehicle model on matlab simulink

Table 3: Parameters of Li-ion battery

Parameter	Values
Rated capacity	20Ah
Battery constant voltage E_0	232.926 V
Polarization constant K	0.06068 V/(Ah)
Internal resistance R_{bat}	0.1075Ω
Time constant (I^*)	30s
Ez amplitude A	18.266 V
Ez time constant inverse B	1.531 Ah– 1

In figure 2, we present the global system implemented in MATLAB/SIMULINK. The cited previous blocs as components and controllers are connected to build the overall system. After simulation action the obtained results are shown respectively: Figure 3 is for the vehicle speed, as reference and real speed in an acceleration and deceleration car speed conditions. Here we touch the 150Km/h. We notice that the speed follows the reference speed. Then, figure 4 is for the angular velocity of the wheels which is proportional to the shaft angular velocity of the electric machine. In figure 5, the response of PMSM angular velocity is presented. When the reference speed was fixed in 100 Km/h; the speed controller needs 0.1 s to reach the reference. The response time is stumpy and the system is robustly stable and precise. Figure 6 shows the electromagnetic torque of the PMSM. The torque variation is inversed to the speed variation. Next, figure 7 is for the angular velocity of PMSG. The speed regulator makes the generator speed fixed at maximum speed. Finally, figure 8 is for the DC link voltage that reaches the references (700V) after 8s. The response is later than the speed response.

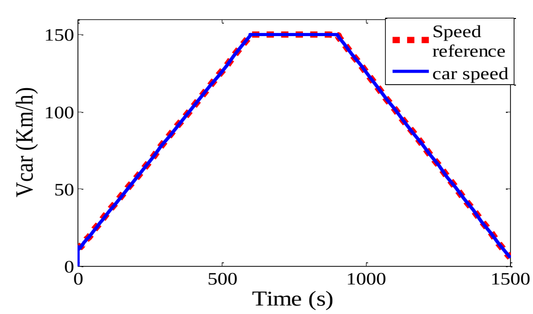

Figure 3: Pursuit of the speed of the car

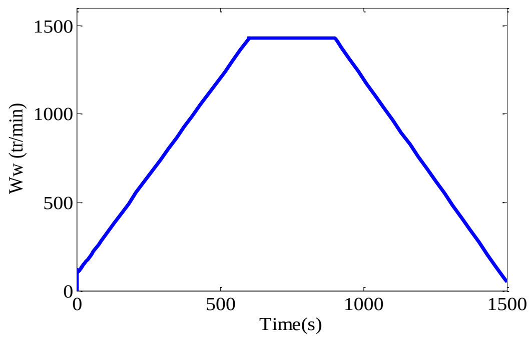

Figure 4: Angular velocity of the wheels

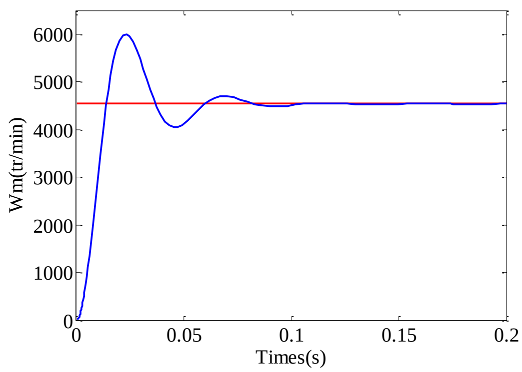

Figure 5: PMSM angular velocity

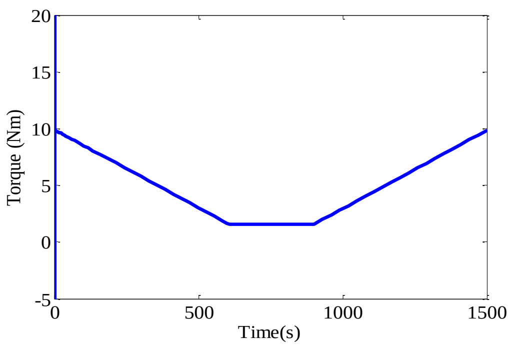

Figure 6: Electromagnetic torque of PMSM

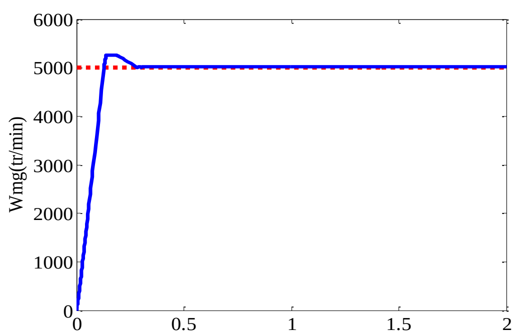

Figure 7: Shaft angular velocity of GMSM

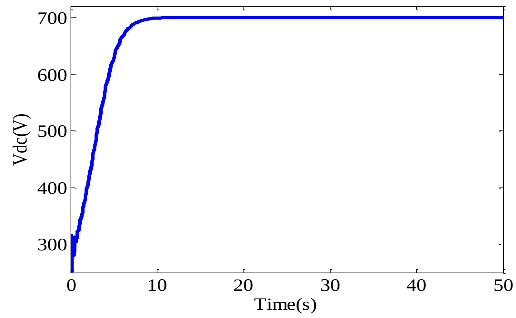

Figure 8: Dc-link voltage

V. CONCLUSIONS

This paper includes a general presentation of hybrid vehicles, their compositions and their types. The mathematical models of each vehicle component are described, modeled, the global control system is built and the corresponding results are presented and discussed. A future works related to this first HEV model can be presented, were the objective is to build an intelligent control method that guarantee the system rapidity and optimize the energy consumption.

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