

Energetic Macroscopic Representation of a Naturally-Aspirated Engine coupled to a salient pole synchronous machine

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Abstract: Hybrid Electric Vehicle (HEV) is considered as the most promising solution to overcome energy crisis and air pollution. To insure an improvement of the vehicle performance and a decrease of pollutant emissions, the design of its powertrain components is necessary. In a project of a hybrid locomotive, the studied railway powertrain admits a diesel engine as a primary source. In this paper, a dynamic model of a Naturally-Aspirated Engine using Energetic Macroscopic Representation (EMR) is presented. To deliver the produced mechanical power to a central Direct Current (DC) bus, a salient pole synchronous machine EMR model is also presented. From EMR models, the Maximum Control Structure (MCS) and then a Practical Control Structure (PCS) to locally control the diesel driven generator set are implemented. In addition to control the power delivered by the system, consumption and CO₂ gas emissions estimations are obtained from these models.

Keywords: Energetic Macroscopic Representation, Maximum Control Structure, naturally-aspired engine, synchronous machine, hybrid locomotive, energy, environment.

1. INTRODUCTION

Due to the inevitable drying up of petroleum reserves, the growing concerns on fuel efficiency and global “warning” (i.e. increase of pollutant emissions and potential increase of global temperature), the use of hybrid systems in vehicular technologies is constantly increasing. Indeed, hybrid vehicles are an essential bridge between oil-based vehicles and electric vehicles (Cousineau 2006). Even if it is a more ecological mean of transport than the air, road or maritime transport, the railway transport is also concerned with its diesel locomotives used for specific tasks (assistance mission, maintenance on catenaries...) (Akli 2007). The French local freight, which represents 40% of the global freight transport, is realized by private operators. They often leave from a non-electrified junction and need to be energetically autonomous. The existing shunting activities are usually performed by locomotives powered by a noisy diesel engine and not stopping when the locomotive is idling. In its activities of locomotives innovation, Alstom Transportation is proposing an advanced solution by adding to the traditional diesel electric propulsion, a battery/ultra capacitors propulsion system, more respectful of the environment. One step of the project is to propose a Matlab/Simulink model of the global system architecture using EMR (Bouscayrol 2005), (Solano 2011).

The first studies about Internal Combustion Engines (ICEs) were realised in 1898 with (Meier 1898). Since then, notable improvements were realised. Engines present higher efficiencies with specific power output and have to respect the imposed emissions regulations (Rakopoulos 2008). The use of exhaust gas recirculation, exhaust gas after treatment

and other achievements has contributed to the development of cleaner diesel engines (Heywood 1998). The development of engine models on simulation proposed in (Lipkea 1994), (Rakopoulos 1995) and (Rakopoulos 1998) permit to deal with the prediction of the engine exhaust emissions trends, with the analysis of gas reactions and formations in the engine and with the improvement of the efficiency of the used engine models in a cycle simulation. However, considering the EMR literature, most of the ICEs models are static ones and do not provide information about the type of fuel injected in. For instance, in (Lhomme 2004), a simple model is used for the ICE and is presented figure 1. In other words, to implement the mechanical behaviour of an ICE (mechanical torque depending on speed velocity of the shaft), cartographies are used. Thus, dynamics are neglected and this kind of model is generally associated with dynamic components such as electric filters, power electronics... This paper presents a dynamic EMR of a Naturally-Aspirated Engine coupled to a salient pole synchronous machine. The proposed model aims to include dynamics and to propose a speed control of the engine.

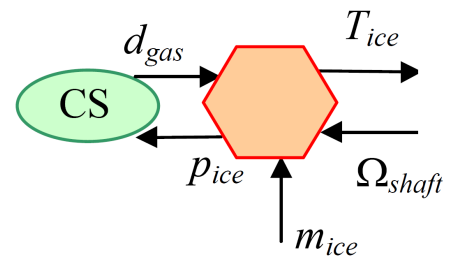


Fig. 1. EMR model of an ICE proposed in (Lhomme 2004)

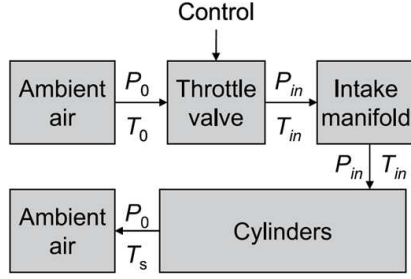


Fig. 2. General structure of a gasoline atmospheric engine (Verdonck 2010)

The atmospheric engine (Fig. 2) proposed in [Verd2010] is the adopted structure for this study. The next section 2 states about equations and EMR/MCS of the atmospheric engine. The section 3 describes the developed model of the salient pole synchronous machine to convert the mechanical power to electric power. Section 4 consists of merging sections 2 and 3 models with simulation results and their representation section 5.

2. EMR AND MCS OF THE ATMOSPHERIC ENGINE

This section is dedicated to the EMR study of the presented atmospheric engine (Fig. 2). Thus, every part of the engine (ambient air, throttle valve, intake manifold and cylinders) is detailed.

2.1 Ambient air (intake part)

Ambient air is considered as a hydraulic source and characterised by a volume flow rate (\dot{m}_{air}) and a pressure (P_{im}).

2.2 Throttle valve

The throttle valve is not directly represented here. In that case, this element will be taken into account in the subsection 2.8 using MCS.

2.3 Intake manifold

The simulation models the intake manifold as a differential equation for the pressure. The difference in the incoming and outgoing mass flow rates represents the net rate of change of air mass with respect to time. This quantity, according to the ideal gas law, is proportional to the time derivative of the manifold pressure. Thus, it corresponds to an element of accumulation using the EMR formalism. With this approach the differential equation for the pressure P_{im} in the volume V_{im} is:

$$\frac{dP_{im}(t)}{dt} = \frac{RT_{im}}{V_{im}} (\dot{m}_{air}(t) - \dot{m}_{cyl}(t)) \quad (1)$$

with R , the ideal gas constant, \dot{m}_{air} and \dot{m}_{cyl} represent the inlet and outlet mass flows respectively. In this model, the temperature is assumed as constant. As described in (Chrenko 2008), a gas flow presents at the same time thermal and pneumatic energies. A separation between these domains

cannot be done. A change in the gas composition (chemical reaction consequence) changes the internal energy. Thus, the temperature is influenced too. If the choice of the variables does not comply with the general EMR approach (use of two variables), its application might be called pseudo-EMR and would need more than two variables.

2.4 Fuel tank

The fuel is considered as a hydraulic source too. In order to characterise the nature of fuel which is injected in cylinders, its heating value and more specifically its Lower Heating Value (LHV) in J/kg is coupled with a mass flow rate (\dot{m}_{fuel}). The heating value or energy value of a substance, usually a fuel, is the amount of heat released during the combustion of a specified amount of it. The energy value is a characteristic for each substance. It is measured in units of energy per unit of the substance.

2.5 Cylinders

Cylinders mix the intake manifold air (P_{im} and \dot{m}_{cyl} variables) and the fuel (\dot{m}_{fuel} and LHV variables) provided by a tank. The reaction of combustion produces exhaust gases (\dot{m}_{exh} and P_{air} variables) and a mechanical power (T_{cyl} and Ω_{shaft} variables). Because a hydraulic power is converted in a mechanical power, cylinders are represented by a multi-physics element of conversion. Equation (2) gives the mathematical expressions of the mechanical torque and the intake volume flow rate.

$$\begin{cases} T_{cyl} = \frac{1}{\Omega_{shaft}} \left(\eta_{ind} \dot{m}_{fuel} LHV - \frac{\Omega_{shaft}}{4\pi} V_{ed} (P_{air} - P_{im}) \right) \\ \dot{m}_{cyl} = \frac{P_{im}}{RT_{im}} \eta_v \frac{\Omega_{shaft}}{4\pi} V_{ed} \end{cases} \quad (2)$$

with V_{ed} the engine displacement, η_{ind} the global (fuel-torque) efficiency and η_v the volumetric efficiency. The volume flow rate of exhaust gases (\dot{m}_{exh}) is considered as the sum of the intake volume flow rate (\dot{m}_{cyl}) with the fuel volume flow rate (initial fuel mass flow rate \dot{m}_{fuel} converted in volume flow rate using the density of the considered fuel).

2.6 Ambient air (exhaust part)

Ambient air is also considered as a hydraulic source.

2.7 Mechanical shaft

A mechanical shaft is required to transmit the mechanical power to the synchronous salient pole machine. Its EMR modelling is represented by an element of accumulation and takes into account: the inertia of the shaft (J), the friction forces (f_{shaft}) (equation (3)).

$$J \frac{d\Omega_{shaft}(t)}{dt} = T_{cyl}(t) - T_{load}(t) - f_{shaft} \Omega_{shaft}(t) \quad (3)$$

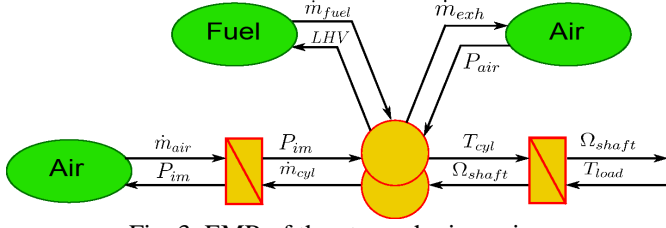


Fig. 3. EMR of the atmospheric engine

2.8 MCS of the atmospheric engine

The MCS' aim of the atmospheric engine is to control the rotational speed of the mechanical shaft. Thus, the use of a first PI controller permits to control the torque produced by the cylinders from the shaft speed reference. The difficulty of this tuning chain lies in the reversal of the cylinders' equations. A downstream coupling block must be reversed. This kind of block combines at least two inputs in a single output. In terms of control, a single reference has to induce two output references. In such a case, a distribution factor k_{rep} shares out the input reference ($T_{cyl,ref}$) between the two output references ($P_{im,ref}$ and $\dot{m}_{fuel,ref}$).

$$\begin{cases} P_{im,ref} = P_{air} + \frac{4\pi}{V_{ed}}(1 - k_{rep})T_{cyl,ref} \\ \dot{m}_{fuel,ref} = \frac{1}{LHV\eta_{ind}}\Omega_{shaft}T_{cyl,ref}k_{rep} \end{cases} \quad (4)$$

The repartition factor value is set to 1. Because the studied engine is an atmospheric engine, it means that the pressure in the intake manifold is equal to the air pressure. Setting k_{rep} equal to one, equation (4) implies $P_{im,ref} = P_{air}$ and equation (5).

$$\dot{m}_{fuel,ref} = \frac{1}{LHV\eta_{ind}}\Omega_{shaft}T_{cyl,ref} \quad (5)$$

Finally, a second PI controller controls the air flow to impose ($\dot{m}_{air,ref}$).

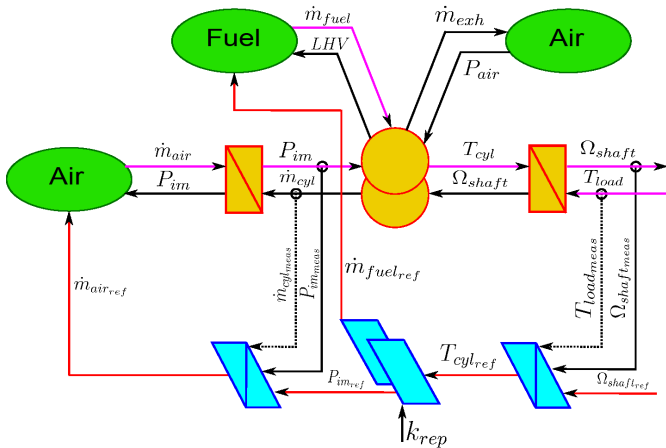


Fig. 4. MCS of the atmospheric engine

3. EMR AND MCS OF THE ALTERNATOR

3.1 The d-q synchronous reference frame

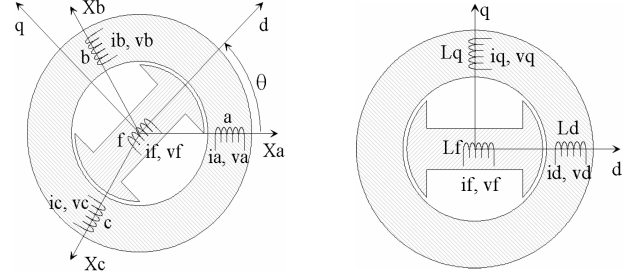


Fig. 5. Model of the synchronous machine in the three phase frame (left side) and Park frame (right side)

Equations which govern a three phase alternative machine depend on resistances, inductances and mutual inductances of its rotor and its stator. Those mutual inductances are linked to the relative position of the rotor with the stator. Thus, to simplify differential equations, it is easier to work in the d-q frame than in the three phase one. To obtain a constant mutual inductance, Concordia and Park transformations are used. It permits to express the three currents, voltages and flux of the stator (a_s, b_s, c_s frame) and of the rotor (a_r, b_r, c_r frame) in a frame linked to the rotary field (d-q frame). Considering voltages, currents and flux three phase components as X_a, X_b, X_c and as X_d, X_q in the d-q frame, Park (equation 1) and Concordia transformations permit to work in the two frames.

$$\begin{bmatrix} X_d \\ X_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\Pi}{3}\right) & \cos\left(\theta + \frac{2\Pi}{3}\right) \\ -\sin(\theta) & -\sin\left(\theta - \frac{2\Pi}{3}\right) & -\sin\left(\theta + \frac{2\Pi}{3}\right) \end{bmatrix} \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \quad (6)$$

3.2 Equations and EMR of the salient pole synchronous machine

The machine corresponds to the figure 5 in the three phase frame (left side) and in the Park frame (right side). Equations 7, 8 and 9 are the electromechanical torque T_{load} , the magnetic flows (Φ_d, Φ_q and Φ_f) and the voltages (V_d, V_q and V_f) equations of the electric machine depending on the shaft rotational speed Ω_{shaft} , armatures resistances (R_s and R_f) inductances (L_d, L_q and L_f), mutual inductance (M) and the number of pole pair (P).

$$T_{load} = p(\Phi_d I_q - \Phi_q I_d) \quad (7)$$

$$\begin{cases} \Phi_d = L_d I_d + M I_f \\ \Phi_q = L_q I_q \\ \Phi_f = L_f I_f + M I_d \end{cases} \quad (8)$$

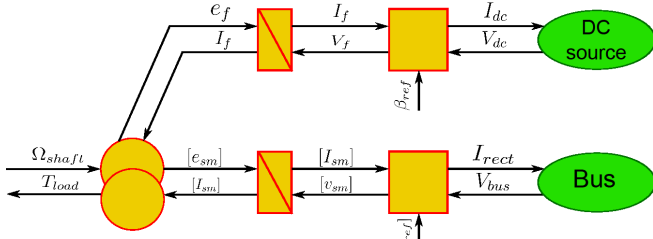


Fig. 6. EMR of the alternator

$$\begin{cases} V_d = R_s I_d + \frac{d\Phi_d}{dt} - \Omega_{shaft} \Phi_q \\ V_q = R_s I_q + \frac{d\Phi_q}{dt} + \Omega_{shaft} \Phi_d \\ V_f = R_f I_f + \frac{d\Phi_f}{dt} \end{cases} \quad (9)$$

From equations (7) and (8), electromotive forces (e_d and e_q) are expressed (equation (10)).

$$\begin{cases} e_d = -\Omega_{shaft} L_q I_q + M \frac{dI_f}{dt} \\ e_q = \Omega_{shaft} (L_d I_d + M I_f) \end{cases} \quad (10)$$

Interdependence between d and q axis variables clearly appears. Thus, using temporary variables (V'_d and V'_q), V_d (V_q) voltage can be defined as the sum of V'_d (V'_q) and e_d (e_q) voltages. From this operation, currents' dynamics are modelled under a transfer function form (equation 11).

$$\begin{cases} \frac{I_d(s)}{V'_d(s)} = \frac{1}{R_s} \frac{1}{1 + \frac{L_d}{R_s} s} \\ \frac{I_q(s)}{V'_q(s)} = \frac{1}{R_s} \frac{1}{1 + \frac{L_q}{R_s} s} \end{cases} \quad (11)$$

The same work is realised to solve the d-q coupling in f frame.

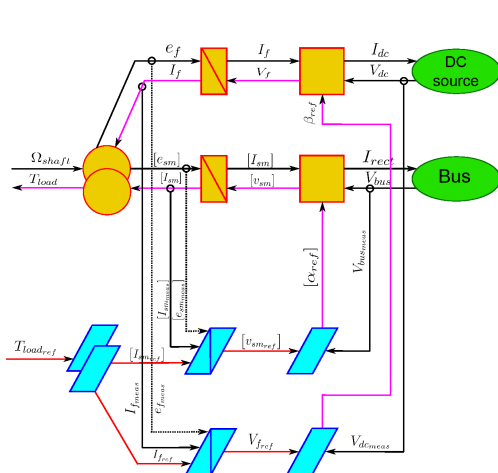


Fig. 7. MCS of the alternator

3.3 MCS of the salient pole synchronous machine

The goal of the alternator MCS is to control the torque (T_{load}) using the two available degrees of freedom (β_{ref} and α_{ref}). The control chain is deduced from the setting chain. Thus, MCS presents an element of repartition to share out currents' references. The problem of this bloc is to obtain three references (currents) from one reference (torque). In reality, the torque is not the only reference to be imposed. Magnetic flux (Φ_d and Φ_q) are also imposed and coupled with the torque to deduce the three currents' references. The principle is to take the defluxing characteristic of the machine and to work on its maximum flux (Φ_{ref} , equation 12).

$$I_{ref} = \frac{T_{load,ref}}{p \Phi_{ref}} \quad (12)$$

The real flux (ϕ , equation 13) is a combination of the magnetic flux along d-q axis.

$$\phi = \sqrt{\phi_d^2 + \phi_q^2} \quad (13)$$

Taking into account the load angle δ , windings' currents along d and q axis and inductor's current references are deduced thanks to equation 14.

$$\begin{cases} I_{d,ref} = -I_{ref} \sin \delta \\ I_{q,ref} = I_{ref} \cos \delta \\ I_{f,ref} = \frac{\sqrt{\Phi_{ref}^2 - (L_q I_{q,ref})^2} - L_q I_{d,ref}}{M} \end{cases} \quad (14)$$

Three PI controllers permit to control three voltages (V_d , V_q and V_f) from three currents (I_d , I_q and I_f). Finally, the inversion of rectifiers result in the control of transformation ratios, degrees of freedom of the system.

3.4 Estimation of the load torque and the electromotive forces

Because electromotive forces cannot be directly measured and because of the torque sensors' cost, a block of estimation (figure 8) is used to estimate $[e_{dq}]$, e_f and T_{load} . Concerned equations are equations 7 and 10.

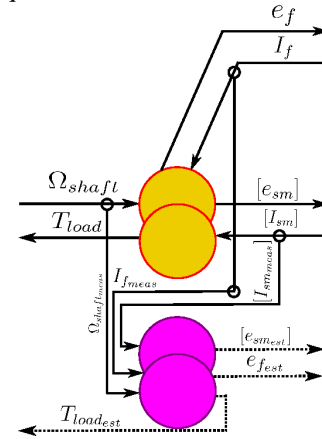


Fig. 8. Estimation of the load torque and the electromotive forces

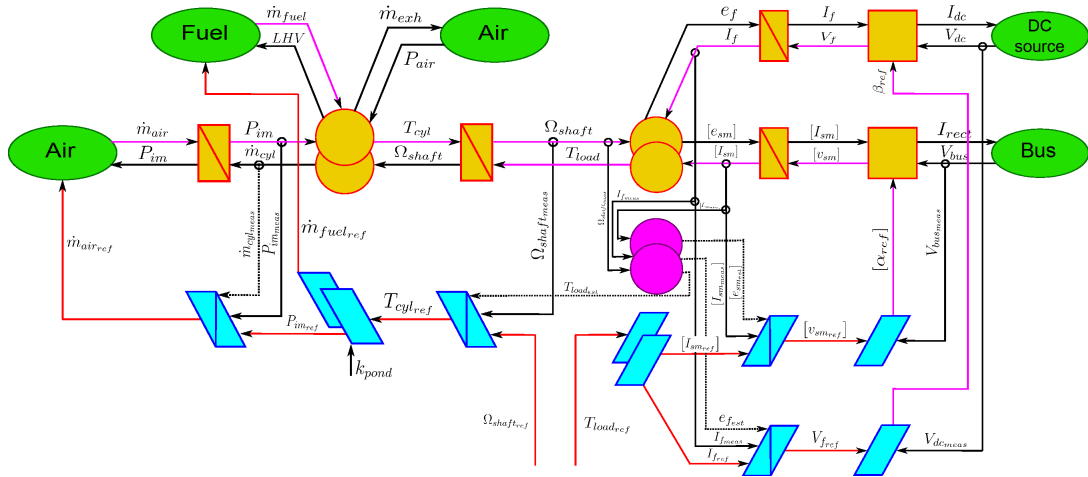


Fig. 9. EMR and PCS of the ICE

4. EMR AND MCS OF THE ICE

The diesel driven generator EMR is made up of the two previous presented models developed on figures 4 and 7. The control of the mechanical power at the output of the shaft permits to control the electrical power delivered by the synchronous machine, depending on its losses.

5. RESULTS

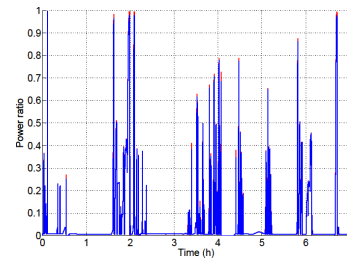


Fig. 16. Evolution of the power mission reference ratio (red) and the electric power ratio (blue) according to time

Presented results on figures 10 to 16 were obtained using the most restricting mission as an input. The results of the figure 10 permit to confirm that the pressure of the air into the intake manifold is equal to 1 bar like in a real atmospheric engine. Figures 11, 14 and 15 give an approximation of:

- the volume flow of the fuel at the intake,
- the corresponding volume of fuel used,
- the mass of exhaust carbon dioxide gas during the mission.

The volume of fuel is obtained thanks to an integration of the volume flow at the intake. From this volume (around 90L), the CO_2 mass product is deduced. Indeed, one litre of fuel produces around 2.662 kg of CO_2 . Thus, around 250 kg of CO_2 are emitted for the considered power mission. Moreover, the figure 16 informs that the mechanical power mission of reference is converted into an electric power provided to the central DC bus thanks to the synchronous machine. To check the good efficiency of the control of the ICE, a mechanical torque and a rotational speed references were applied to the shaft. On figures 12 and 13, references and model responses are represented in accordance with the key.

6. CONCLUSIONS

In this paper, a novel EMR/MCS/PCS modelling of a diesel driven generator set has been proposed. Implemented models using Matlab/Simulink take into account:

- the dynamics of a naturally aspirated engine and of a salient pole synchronous machine,
- the nature of the used fuel using its LHV,

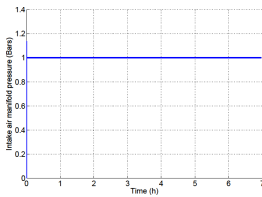


Fig. 10. Evolution of the intake air pressure according to time

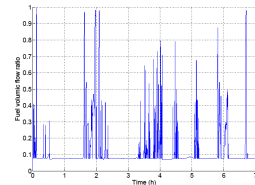


Fig. 11. Evolution of the fuel volume flow ratio according to time

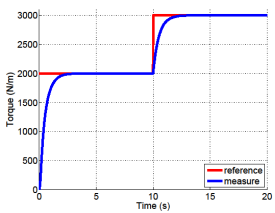


Fig. 12. Evolution of the mechanical torque of the shaft according to a reference

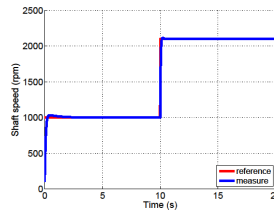


Fig. 13. Evolution of the rotational speed of the shaft according to a reference

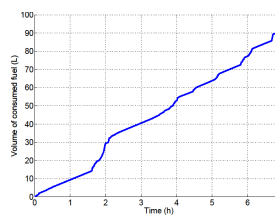


Fig. 14. Evolution of the fuel consumption according to time

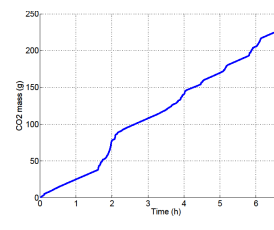


Fig. 15. Evolution of the CO_2 mass product according to time

- estimations of the CO₂ mass product and the consumption of fuel of the atmospheric engine,
- a control of the mechanical power and indirectly the electrical power delivered depending on the alternator losses.

Presented simulation results and their interpretation in the results section prove the good effectiveness of the realised work. The model will be integrated in the global architecture of the hybrid locomotive as a primary source with dynamical batteries and ultra-capacitors EMR models. A future energy management strategy of the system to share out power demand of the vehicle between sources has to be developed. Contrary to actual energy management strategies based on a static model of the ICE, this one will have to take into account dynamical behaviours of the ICE.

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Appendix A. EMR SYNOPTIC

