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Teaching Electric Vehicle drive control using Energetic Macroscopic Representation

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Abstract

The study of an electric vehicle is an attractive topic for students. At the University of Lille1 (France), an electric car is used to teach and develop drive control skills. From software simulation and Hardware-in-the-loop simulation, the students in electrical engineering learn drive control steps with a real electric vehicle. In this paper, the Energetic Macroscopic Representation is used to describe the electric car. This graphical tool allows the decomposition of the studied vehicle in accordance with physical laws. The control scheme is then deduced from the description using the inversion-based control rules.

Keywords: education, hardware-in-the-loop (HIL), EMR, traction control, ZEV (zero emission vehicle)

1 Introduction

Drive control is an important unit in electrical engineers teaching [1] [2]. The development of Electric Vehicle (EV) field is rising up [3], and establishment of drive control is often difficult because several physical fields are in interaction. Several knowledge in multiple scientific fields are necessary for its study, and, due to the complexity and non-flexible platform, only simulation units are often used. However, experimental skills have also to be developed in experimental experience by the future engineers [4].

Energetic Macroscopic Representation (EMR) was introduced in 2000 for research development in complex electromechanical systems. Using the action-reaction principle, this graphical description organizes the system as interconnected sub-systems according to the integral causality. An inversion of this graphical description yields the control structure with controllers and measurements information [8]. EMR is taught in France (Lille, Belfort, Paris), Canada (Trois Rivières), Switzerland (Lausanne) and Spain (Barcelona).

Until today, a first step of simulation initiation on the drive control using EMR was teaching at the University of Lille1 for electrical Master Students. A teaching unit based on EMR with simulation of a fictive Peugeot 106 electric vehicle was proposed for developing basic knowledge on control drive [5]. In this paper, in association with an experimental platform and the real Tazzari Zero EV [6], a drive control teaching method using a real electric car application and EMR formalism is presented. First, the studied vehicle modeling is developed. The EMR of the system is then described. The whole control structure is obtained using the inversion based rules of EMR. In a fourth step, by using the EMR library, the transposition of the EMR scheme to MATLAB-Simulink allows a fast simulation model development. Finally, a Hardware-In-the-Loop (HIL) simulation of the electric vehicle is deduced by using a DC machine for the traction drive. A synchronous machine is used to emulate the mechanical behaviour. The students can then validated their simulation control drive with the help of a teacher.

2 Studied vehicle

A teaching unit "Control of electrical drives using EMR" has been introduced in the electrical Master degree of Lille. The unit is composed of 10h of lectures, 12h of exercises, 12h of practical works in laboratory and 16h for a simulation project. This unit is associated with 5 ECTS (European Credit Transfer System). In this paper, the simulation project is presented, based on the study of a real electric vehicle: the Tazzari Zero (Fig. 1).

2.1 Description of the vehicle and drive to test

The studied EV is a Tazzari Zero equipped with a gearbox, a differential and two driven-wheels. The propulsion system is composed of a 15 kW induction machine fed by a 80 V-160 Ah Lithium Iron Phosphate (LiFePO4) battery. Before the study, the Tazzari Zero EV is presented to the students. The students with a driver's license may drive and test the vehicle. Problematic like hardware footprint, safety, and passenger comfort are then set. In this unit, in order to simplify the study, the induction machine is replaced by a permanent magnet DC machine supplied by a chopper from the battery (Fig. 2). What is more, the students must take several assumptions: the regenerative braking is assumed sufficient to stop the vehicle, the mechanical braking is then not taken account.

Figure 1 : Studied Tazzari Zero EV

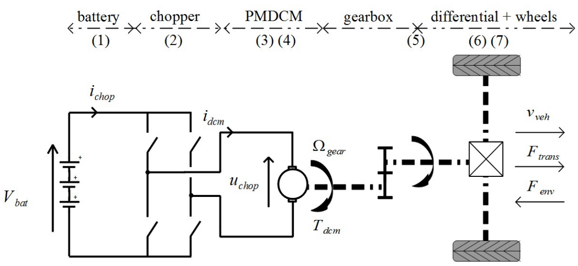

Figure 2: Simplified traction system scheme of the studied EV

2.2 Modeling of the vehicle

Each element of the EV can be modelled by mathematical relationships. All of them were previously studied in different lectures.

The battery is considered as an equivalent capacitor (no losses, linear charge and discharge), which delivers the battery voltage V_{bat}:

$$i_{chop} = C_{eq} \frac{d}{dt} V_{bat} \qquad (1)$$

with C_{eq} the equivalent capacitance of the battery.

The chopper leads to the chopper voltage u_{chop} from the battery voltage V_{bat} and the current i_{chop} from the DC machine current i_{dcm}:

$$\begin{cases} u_{chop} = m_{chop} V_{bat} \\ i_{chop} = m_{chop} i_{dcm} \eta_c^k \end{cases} \text{with } k = \begin{cases} -1 \; if \; P > 0 \\ 1 \; if \; P < 0 \end{cases} \qquad (2)$$

where m_{chop} is the modulation ratio and η_c=95% the average efficiency of the chopper.
From the armature winding of the DC machine, the armature current i_{dcm} is deduced from the chopper voltage u_{chop} and the electromotive force (e.m.f) e_{dcm}.

$$L_{arm} \frac{d}{dt} i_{dcm} = u_{chop} - e_{dcm} - R_{arm} i_{dcm} \qquad (3)$$

where L_{arm} and R_{arm} are the inductance and resistance of the windings. With the electro-mechanical relationship (4), the torque T_{dcm} and the *e.m.f* of the DC machine are obtained from the machine current i_{dcm} and the rotation speed Ω_{gear}.

$$\begin{cases} T_{dcm} = k_{dcm} i_{dcm} \\ e_{dcm} = k_{dcm} \Omega_{gear} \end{cases} \qquad (4)$$

where k_{dcm} is the torque coefficient of the electro-mechanical conversion.

For the study, it is considered that the vehicle is driven on straight lines and that the contact between the wheels and the road is neglected. Both asumptions allow to represent the mechanical differentials plus the wheels as one equivalent wheel. The mechanical transmission is then modeled with the gearbox and one equivalent wheel:

$$\begin{cases} F_{trans} = (k_g / R_w) T_{dcm} \eta_g^n \\ \Omega_{gear} = (k_g / R_w) v_{veh} \end{cases} \qquad (5)$$

$$\text{with } n = \begin{cases} 1 \; if \; P > 0 \\ -1 \; if \; P < 0 \end{cases}$$

where k_g is the gearbox ratio, R_w the radius of the wheel, and η_g=92% the constant gearbox efficiency.

The chassis is considered as an equivalent total mass M_{tot} (mass of the EV and the equivalent masses of the rotating part). The vehicle velocity v_{veh} is obtained by using the Newton's second law with the transmission and environment forces, F_{trans} and F_{env}:

$$M_{tot}\frac{d}{dt}v_{veh}=F_{trans}-F_{env} \qquad (6)$$

The environment force is composed of a rolling force, an aerodynamic force and the grade force:

$$F_{env}=F_0+A\,v_{veh}+B\,v_{veh}^2+M_{tot}\,g\sin\alpha \qquad (7)$$

with F_0 the initial rolling force, A the rolling coefficient, B the aerodynamic coefficient, α the slop rate and g the gravity.

3 Electric vehicle representation

3.1 EMR fundamentals

By a systemic approach, the objective of EMR is to establish a functional description of an energetic system for its control. It describes the energy exchange between components of a system following two principles [7]:

- the interaction principle: the system is broken down into basic subsystems connecting each other following the action-reaction principle (see appendix): energy sources (green ovals), accumulation elements (orange rectangles), conversion elements without energy accumulation (orange circle for multiphysical conversion and orange square for monophysical conversion) and coupling elements for energy distribution (orange overlapped pictograms). The product of action-reaction variables between each component represents the instantaneous power exchanged.
- the causality principle : the internal relationship of each element are based on the mathematical causality principle. The accumulation elements represent energy accumulation, the relationships between their inputs and outputs are integral (integral causality). It should be noted that, for the conversion element, the internal relationships are independent of time.

By inversion of the EMR model, the inversion-based control is built. Direct inversion of the mathematical model is done for the conversion elements. The inversion of accumulation elements requires a controller and different measurements.

3.2 EMR and deduced control of studied EV

From the relationships and assumptions (no mechanical braking for example), the students must deduce the EMR of the studied vehicle. First, each components are connected each other in respect with the interaction principle.

The battery and environment are respectively electrical and mechanical sources (green oval pictograms), which lead to the battery voltage V_{bat} and the environment force F_{env}. The chopper and the mechanical transmission are monophysical conversion described by the orange square pictograms. The DC machine is a multiphysical element described by an orange circle pictogram. The armature winding and the chassis are accumulation elements, which are described by orange cross rectangle pictograms. They lead the armature current i_{dcm} and v_{veh} as state variables. The EMR of the EV is depicted in Fig. 4.

3.3 Inversion based control of studied EV

In a second step, to ensure the desired vehicle speed, the students must deduce the tuning path. The tuning path link the tuning variable (m_{chop}) to the variable to be controlled (v_{veh}) (Fig. 3).

$$\begin{array}{l} u_{chop} \longrightarrow i_{dcm} \longrightarrow T_{dcm} \longrightarrow F_{trans} \longrightarrow v_{veh} \\ \uparrow \\ m_{chop} \end{array}$$

Figure 3: Tuning path of the Tazzari EV

The control structure is then deduced from the EMR using inversion-based rules (lower part of

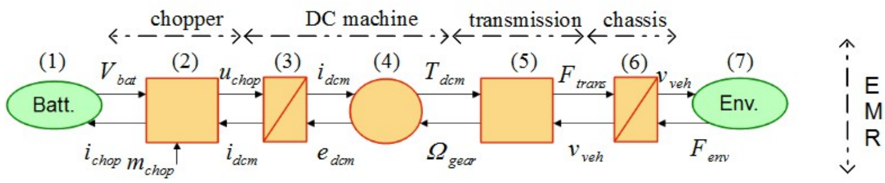

Figure 4: EMR of the studied EV

the Fig. 7). For the first simulation step, all variables are considered measurable.

The relationship (2) is directly inverted to obtain the reference chopper modulation ratio m_{chop} from the reference chopper voltage u_{chop} and the measured battery voltage V_{bat}:

$$m_{ref} = \frac{u_{chop\_ref}}{V_{bat\_mea}} \quad (8)$$

The inversion of (3) requires a current controller to provide the chopper voltage u_{chop} from the reference current i_{dcm_ref}, the measured current i_{dcm_mea} and the measured $e.m.f$.

$$u_{chop\_ref} = C[i_{dcm\_ref} - i_{dcm\_mea}] + e_{dcm\_mea} \quad (9)$$

where $C[X_{ref}\text{-}X_{mea}]$ is a controller (P, PI or other kind of controllers).

The relationship (4) and (5) are then inverted to obtain the reference DC machine current i_{dcm_ref} from the transmission force F_{trans_ref}:

$$i_{dcm\_ref} = \frac{T_{dcm\_ref}}{k_{dcm}} \quad (10)$$

$$T_{dcm\_ref} = \frac{F_{trans\_ref}}{(k_g / R_w)} \quad (11)$$

Finally, from the reference vehicle velocity v_{veh_ref}, the measured vehicle velocity v_{veh_mea} and the measured environment force F_{env_mea}, the reference transmission force F_{trans_ref} is provided from (6), by using a controller:

$$F_{trans\_ref} = C[v_{veh\_ref} - v_{veh\_mea}] + F_{env\_mea} \quad (12)$$

The EMR and its deduced control structure are depicted in the Fig. 7.

4 Simulation and HIL simulation

In this step, the students must do the simulation model of the simplified Tazzari Zero EV, determine the whole control structure, tune all controllers and implement the control part in a simulation software.

4.1 Simulation of studied vehicle

The EMR and the control scheme of the vehicle are implemented to MATLAB-Simulink, which is chosen as simulation software. Two programs help the students for this implementation: an initialisation program, which contains all vehicle parameters (battery capacity, gearbox ratio, mass…) and an EMR Simulink library with basic elements [8] (Fig. 5).

The simulation part is composed of 4 sessions of 4h each in a simulation room on a supervision of a teacher. The first sessions are dedicated to modelling and the remaining to the control. In the EMR philosophy, each element is tested alone before its connection with other subsystems. Controls block are then tested with their associated model elements to check if the inversion function is well designed. Most of the students (75%) [5] develop the whole Simulink program (Fig. 6). Afterwards, they can simulate their system with an Urban Driving Cycle (UDC). Some simulation

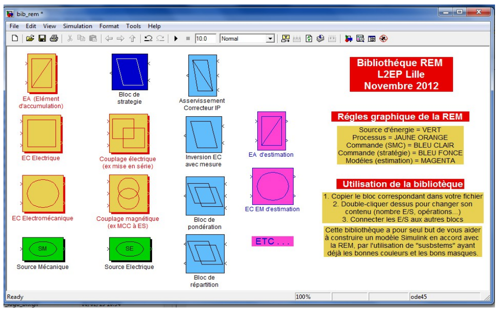

Figure 5: EMR library into MATLAB-Simulink

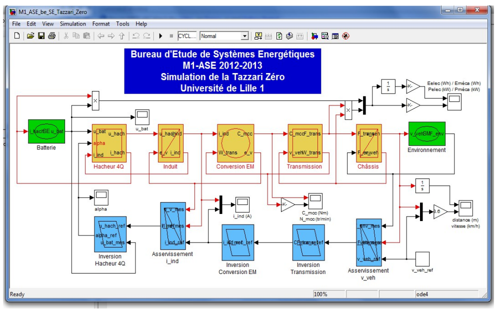

Figure 6: MATLAB-Simulink model of the studied EV

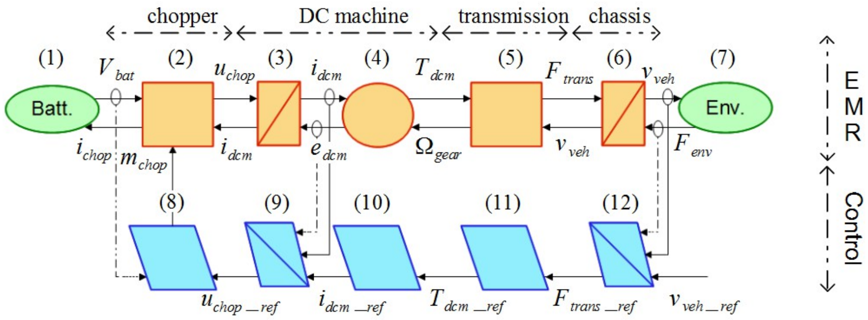

Figure 7: EMR and deduced control of the studied EV

results can be analysed, the vehicle speed (Fig. 8) and the machine torque (Fig. 9) for example. Advanced students (10%) can extend their simulation program by a PWM of the chopper, or using a DC machine with field winding.

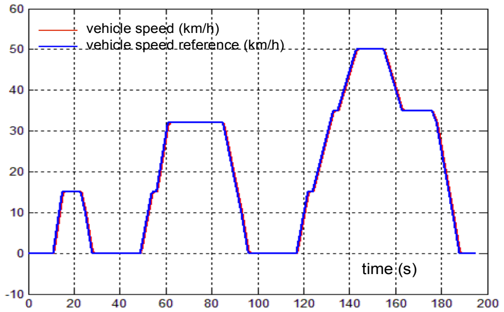

Figure 8: Simulation vehicle speed (UDC)

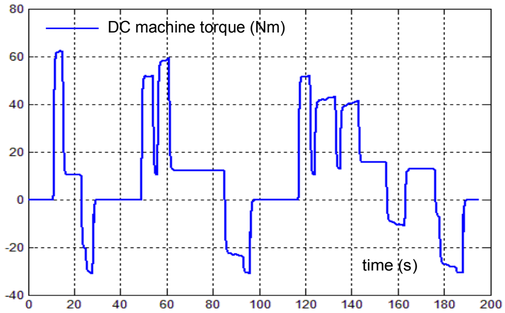

Figure 9: Simulation PMDCM torque (UDC)

The students fill in an assessment sheet for each session in order to evaluate the evolution of their project. A project report including the simulation program have to be done at the end of the unit.
It appears that modeling of the system is the most difficult part because students have to connect concepts from different physical fields. The control structure is in fact easily obtained using the inversion-based control.

4.2 HIL simulation

At the University of Lille1, the students can extend their experience and control implementation skills on electric vehicle with a real time application. Generaly, control structure is tested with static application. The University of Lille1 proposed to use the HIL concept with a real-power setup and a dSPACE controller board [9][10] in a dedicated real-time validation platform (Fig. 10).

The system is split into a mechanical power train and a 10 kW permanent magnet DC machine, linked by the rotation speed Ω_{gear} and the DC torque T_{dcm}. To focus on the electrical part, a 10 kW synchronous machine and its control replaces the mechanical part of the EV (Fig. 11). It must imposes the same rotation speed as the mechanical power train $\Omega_{sm} = \Omega_{gear}$. The estimated torque T_{dcm_est} is imposed on the mechanical model of the vehicle (purple block), which reacts by generating the gear referenced speed $\Omega_{gear\_ref} = \Omega_{sm\_ref}$ to the shaft control block. Thus, the synchronous machine reproduces the same behavior as the mechanical part of the Tazzari Zero (transmission, chassis and environment). Electro-mechanical propulsion is fed by a DC bus, which imposes the same battery voltage V_{bat} as the simulation program. The EMR of the HIL simulation system is depicted in Fig. 11.
For the control loop, the electromotive force e_{dcm} and the DC machine torque T_{dcm} can be estimated from measured i_{dcm_mea} and the DC machine rotational speed Ω_{gear_mea} with mathematical relationship (4).

$$\begin{cases} T_{dcm\_est} = k_{dcm} \, i_{dcm\_mea} \\ e_{dcm\_est} = k_{dcm} \, \Omega_{gear\_mea} \end{cases} \quad (13)$$

The best student control structure is implemented and built in the dSPACE controller board (Fig. 12). This implementation and demonstration are done in front of all the students. Simple calibration of the real DC machine parameters is carried-out. Problematic like safety (voltage and currents limits for example), step time of the control structure or PWM frequency are then set. For example, sampling period is set to t_{samp}=500µs in order to ensure good performances. Due to this small sampling period, continuous integrator from simulation are replaced by discrete integrators.
A control panel allow the real-time management (Fig. 13). In this way, comparison between simulation and HIL vehicle speed v_{veh} (Fig. 14) and DC machine torque T_{dcm} (Fig. 15) could be done by students. As simulation results, the HIL simulation vehicle speed v_{veh} follow the speed


Figure 10: electricity and Vehicle (eV) platform

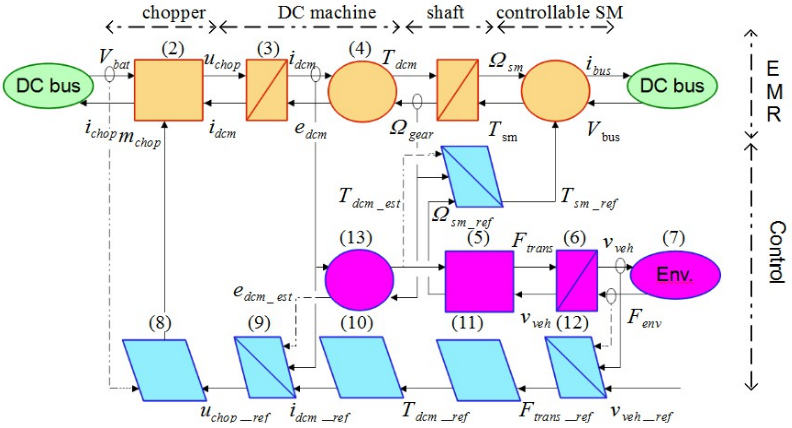

Figure 11: EMR and deduced control of the HIL electric vehicle simulation

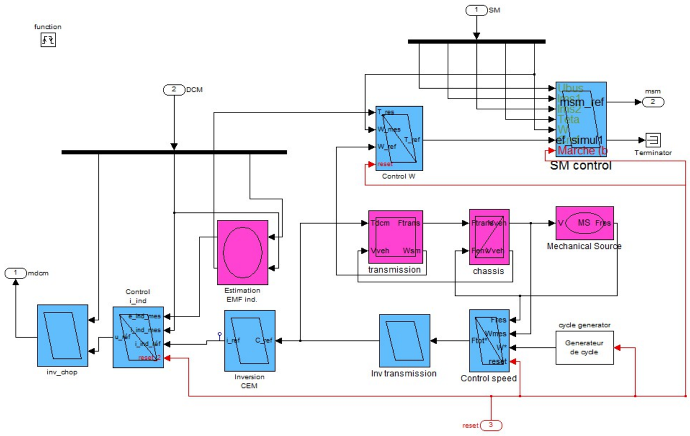

Figure 12: MATLAB-Simulink HIL simulation

reference v_{veh_ref}. The DC machine provides the same torque T_{dcm} as in simulation. The synchronous machine reproduces the same behavior as the mechanical part of the electrical vehicle.

Due to the interest generated by this application, most of the students understood the main concepts of modeling, control, electric vehicle and real-time implementation. Evaluation of this unit show a very good acquisition of fundamentals on drive control, and it generally lead to the best marks in the Master degree.

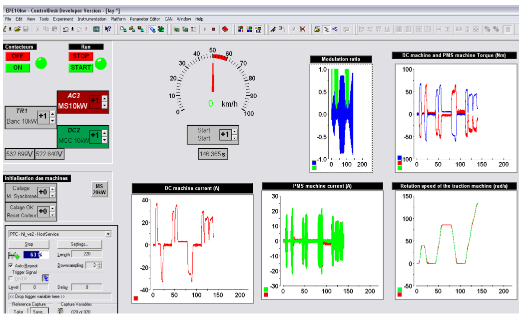
Figure 13: HIL simulation control panel

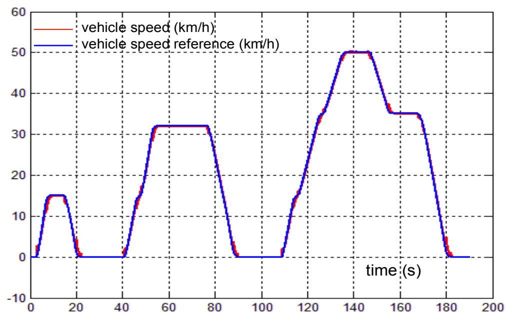

Figure 14: HILvehicle speed (UDC)

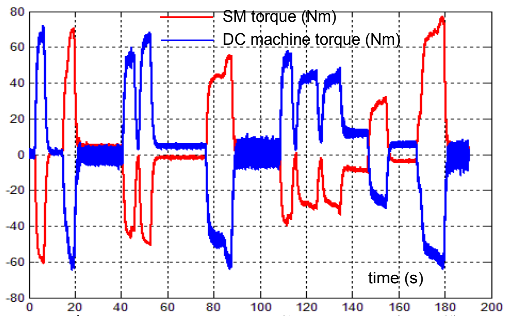

Figure 15: HIL PMDCM torque (UDC)

5 Conclusion

In this paper, a teaching method, using EMR, is presented to define the control scheme of an EV. The real vehicle Tazzari Zero is taking as an example. After driving the vehicle, a first step of simulation into MATLAB-Simulink must be developed by the students. Theoretical drive control knowledge is then developed. A drive control validation via a real-time implementation using HIL simulation is finally presented. A synchronous machine is used to emulate the mechanical part of the EV. Due to the theoretical and real-time concrete application, the students are motivated by this kind of project and a lot of students wish to do this topic the subject of their end-of-year project.

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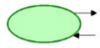
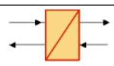
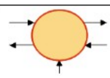
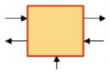
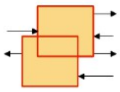
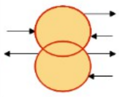
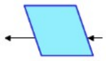
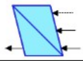
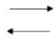
Walter LHOMME received his Master of Science (M.Sc.) degree in 2004, and the Doctor of Philosophy (Ph.D.) degree in 2007, both in Electrical Engineering, from the University of Lille1, France. Since September 2008 he is associate professor at the L2EP of the University of Lille 1. His research activities deal with modelling, control and energy management for hybrid and electric vehicles.

Alain BOUSCAYROL received Ph.D. degree in Electrical Engineering from Institut National Polytechnique de Toulouse, France, in 1995. From 1996 to 2005, he was Associate Professor at University Lille1, Sciences and Technologies, France, where he has been a Professor since 2005. Since 2004, he has managed the national network on Energy Management of Hybrid Electric Vehicles (MEGEVH) France. His research fields deal with EMR and applications.

Appendix : Elements of EMR

	Source of energy		Accumulation element (energy accumulation)		Multiphysical converter (energy conversion)
	Monophysical converter (energy conversion)		Monophysical coupling device (energy conversion)		Multiphysical coupling device (energy conversion)
	Control block without controller		Control block with controller		Action and reaction variables