Project-based Teaching Unit Using Energetic Macroscopic Representation to design drive controllers

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***Abstract*—This paper describes an example of a student's simulation project based on a *steer-by-wire* system. The approach followed during this project relies on the Energetic Macroscopic Representation to help students to organize their simulation worksheet, and to deduce by inversion the control laws.**

I. Introduction

In order to achieve an efficient simulation work, engineers first lay down the scientific description of their systems. Then, they have to organize their equations into a comprehensive and straightforward way, to allow an accurate simulation. Computer code has to be generated to achieve the simulation. For example, one can rely on the Matlab© software to generate their simulation code, and on the Simulink toolbox to use a graphical representation of their system. If the arrangement of the set of equations – ie the graphical description of the system – is clear, then its testing and its analysis are easier and the simulation worksheet may evolve more easily. In addition to this work, engineers should also be able to propose a control algorithm of their system, and point out which measurements should be done.

The capability to realize good simulation worksheets is then an important skills that should be taught to future electrical engineers, in addition to those in other various scientific fields – such as power electronics, electrical machines, mechanics and control. Several practical tools have been developed to describe the system and to propose appropriate control schemes. We find for example the well known *Bond-graph* [1], or the *Causal Ordering graph(COG)* which uses integral causality only [2], [3]. For this last tool, the graphical description of the system are useful to deduce – by inversion – an appropriate control architecture with measurements and controllers.

Energetic Macroscopic Representation(EMR) belongs to the family of graphical description tools which use integral causality only and is based on action reaction principle. Introduced in 2000 for research development in complex electromechanical drives as multi-drives systems[4], the inversion of graphical the description leads to macro-control blocs as used for the control of various applications [5]. Since 2002, EMR is part of the programm of the Master degree shared by the University of Lille and engineering schools of Lille (ENSAM, Ecole Centrale and Polytech'Lille). COG and EMR are used in some other French universities and also at University Québec Trois Rivières (Canada) since 2004 and Ecole Polytechnique Fédérale de Lausanne (Switzerland) since 2005. Indeed these graphical descriptions enable a unified way for causal description of the components of electromechanical systems [5]. Moreover simple inversion rules lead to an easy deduction of the control structure of the studied system. It is then a very useful step for students to develop control of electrical drives [6][7].

The Master degree of University of Lille proposes two teaching units for drive control based on Energetic Macroscopic Representation. The first unit is devoted to an initiation level for developing basic knowledge on drive control and to connect this to other scientific fields[6]. The second unit consists of an expert level to control more complex drives by using more advanced control methodologies. Renewable energy systems and new vehicle applications are particularly studied because they require transversal skills to study such complex system in an efficient way [7]. EMR is then a relevant method to achieve this goal. In this paper, we focus on a student's simulation project of a steer-by-wire system. This system merges two electromagnetic motors and their drives. One is dedicated to control wheel position, while the other provides force-feedback to the driver. With this work, students learn the design process of a simulation program, and they study the interactions between subsystems.

II. EMR Fundamentals

A. Interaction principle

Modelling is made up with several elements which are connected together. Connections hold the evolution of key variables of the system, and thus depicts the interaction between two subsystems [4]. In REM, the orientation of each connection is very important: a variable may act on an element (action) or it may represent its reaction to this action. We define several types of element(figure 1): energy sources (green ovals), accumulation elements (orange rectangles), conversion element without energy accumulation (various pictograms) and coupling elements for energy distribution (orange overlapped pictograms). The elements are connected according to the action and reaction principle using exchange variable (arrows). The

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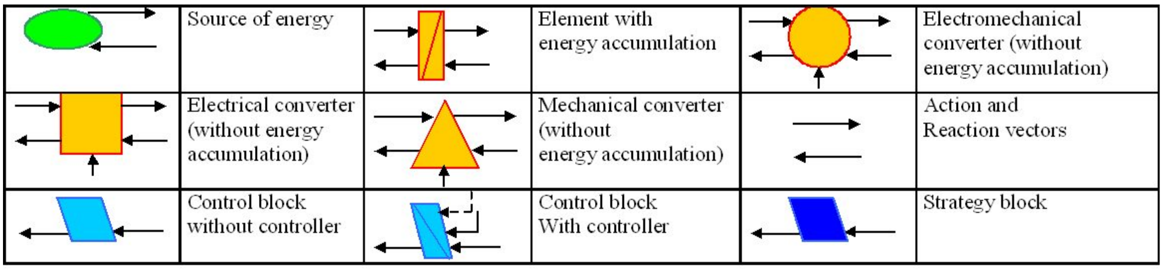

Fig. 1. Elements of EMR, and inversion based control.

product of action and reaction variables between two elements leads to the instantaneous power exchanged.

B. Causality principle

In EMR, we only consider integral causality [2]. Therefore, we can define accumulation elements: these elements encapsulate a time-dependant relationship between its variables: its output is an integral function of its inputs. For example, if the relationship between a variable x and an other y is $x = \dot{y}$, causality principle yields $y = \int x dt$: this shows that y is an output and x is an input of an accumulation element. It induces a delay between y and x. Accumulation rules have been defined to connect elements together, without violating the causality principles. These rules are presented in the expert level unit.

C. Inversion principle

A control scheme helps to find the right input to apply on a system in order to get the desired output (figure 2)[5]. With a system described using EMR, a control scheme can be deduced straight from the inversion of the modelling. We can invert directly relationships without time-dependence (with neither control nor measurement), but cannot invert relationship with time-dependance without violating the causality principle. An indirect inversion, using controllers (control loop) and measurements is then achieved.

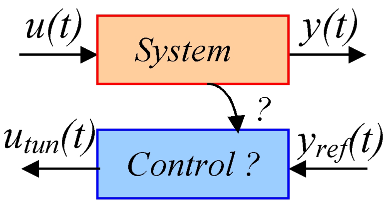

Fig. 2. Inversion principle.

III. EMR and Initiation to Drive Control

A specific unit "Control of electrical drives using EMR" has been introduced in the Master degree of University of Lille. This unit concerns an initiation to drive control using such a graphical tool [6]. The students can improve their skills by choosing a complementary unit "Advanced control of electric systems using EMR". This unit deals with more complex systems (wind energy conversion system, multi-motor traction systems) for an expert level[7]. Each unit is associated with 30 ECTS (European Credit Transfer System). Only the expert level is considered in this paper.

The unit is composed of 12h of lecture on EMR, 16h of seminars on industrial applications, and 24h for a simulation project. Each group of students has to simulate different systems. The studied systems are real industrial applications with different subsystems interconnected. Indeed, this expert level is focused on the associations of sub-systems and the use of ac drives with their control. At the end of the unit the students must be able to model and decompose the system in a physical causal way, and to deduce the control structure of the system by locating controller and measurements or estimations to achieve.

IV. EMR for Simulation of a Steer-by-Wire System

A. System Description

Steer by wire eliminates the mechanical link between a steering wheel and the road wheels. To control position of the road wheels according to steering command, the system first measures steering wheel's angular position. This position serves as an input to a calculator which drives a DC motor in order to place the road wheel at the right position. A small power DC motor is also placed on the steering wheel in order to produce a force feedback to the driver: by this way, he has the information about the steering effort and can have a better control of his vehicle. Steer-by-wire systems bring advantages in terms of safety and comfort, at the condition that the control algorithms is sufficiently stable and reliable, which is a challenge involving many research teams [8][9][10]

The steer-by-wire system is then made up with two DC machines ($M1$ and $M2$ in figure 3), which power is supplied by the same DC Bus E. Two DC-DC converters (which pulse width ratio is named $D1$ and $D2$ respectively) control the voltage applied to the DC machines. In this system, $M2$ is controlled so as to adjust the position of the front train wheels. The position reference is provided by a rotational angle sensor placed on the steering wheel. To provide force-feedback on the steering wheel, we control the motor $M1$ in order to output a torque which is directly calculated from the output torque of $M2$.

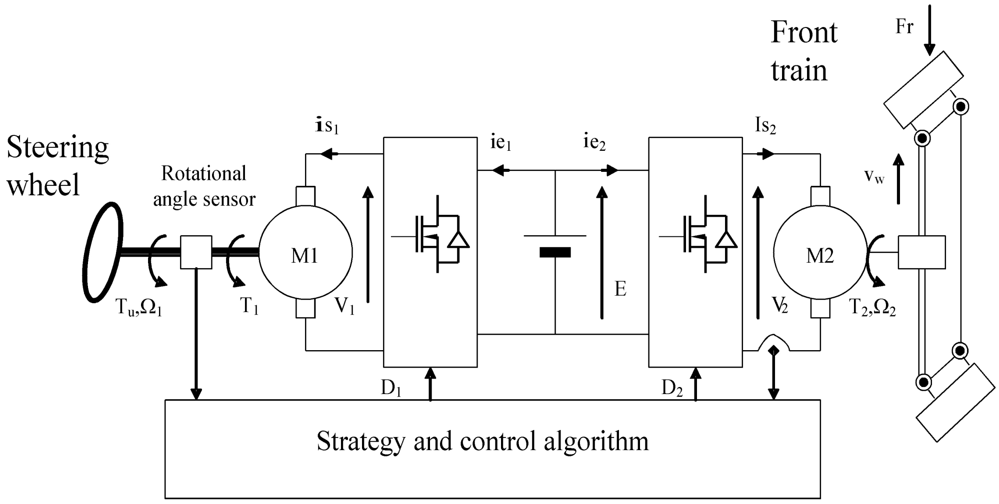

Fig. 3. Example of a simple steer-by-wire system.

B. Simulation requirements

Matlab-Simulink© is chosen as simulation software. The students can use a Simulink library containing the EMR basic elements. The objective of the project is to find a control structure which suits the application. They take care to adjust their controllers' parameters in order to ensure stable operation of each subsystem independently. Then, they look closer to interactions between the two subsystems and how unstable operations may emerge, depending on the force-feedback strategy. Thus they have to deal with mechanical parts, electrical machines, power electronics and automatic control.

C. System's modelling

The students lay down the equations of the system, and organize them according to the causality principle. They can then deduce the EMR, as presented (top of figure 4). The key equations of the system are as follow. First, the vehicle battery is supposed to be an ideal voltage source, E; E is thus an output of a source element depicted by a green oval. We consider the front train drive of figure 3. The DC–DC converter adjust V_2, the voltage supplied to the motor $M2$ and the reaction on the battery is a current i_{e2} calculated from the current flowing in $M2$ called i_{s2}. We have:

$$V_2 = D_2 E \quad (1)$$

$$i_{e2} = D_2 i_{s2} \quad (2)$$

A classical modelling of $M2$, which takes into account the armature inductance L_2 and resistance R_2 and the back emf V_{ind2} is then introduced. This yields to a new equation, which is expressed according to the causality principle:

$$i_{s2} = \frac{1}{L_2} \int (V_2 - V_{ind2} - R_2 i_{s2})\, dt \quad (3)$$

The energy conversion principle inside $M2$ is modelled using a new set of equations:

$$V_{ind2} = K_2 \Omega_2 \quad (4)$$

$$T_2 = K_2 i_{s2} \quad (5)$$

where K_2 is the torque constant of $M2$, Ω_2 is rotor's rotational speed and T_2 is the output torque of $M2$. $M2$ is then described using an accumulation element (3) and a conversion element (4 and 5). The kinematic chain of the front train convert a rotational motion into a translation by using a worm-gear. The transformation involves α, which is the ratio between Ω_2 and v_W, the linear speed of the rod, such as:

$$v_W = \alpha \Omega_2 \quad (6)$$

We suppose that the worm gear system does'nt store energy (kinetic or elastic): the output power of this system is then equal to the mechanical input power. By introducing F_p, the drive force on the tire, the reaction of the crank-connecting rod system on M_2 is then expressed as:

$$T_2 = \alpha F_p \quad (7)$$

One will notice that $T_2 \times \Omega_2 = F_p \times v_w$. Then, a crank-connecting rod system make the tire spinning about a vertical axis. The modelling of this system is given by:

$$\omega_t = \beta v_H \quad (8)$$

$$F_p = \beta T_t \quad (9)$$

with ω_t is the rotational speed of the tires about the vertical axis, and T_t the required torque. The dynamic of the tire about the vertical axis is given by:

$$J_t \frac{d\Omega_t}{dt} = T_t - T_r \quad (10)$$

where J_t is an equivalent inertia and T_r is the reaction of the environment on the tire. An equivalent system modelling is laid down for the other subsystem, but it is not detailed in this paper.

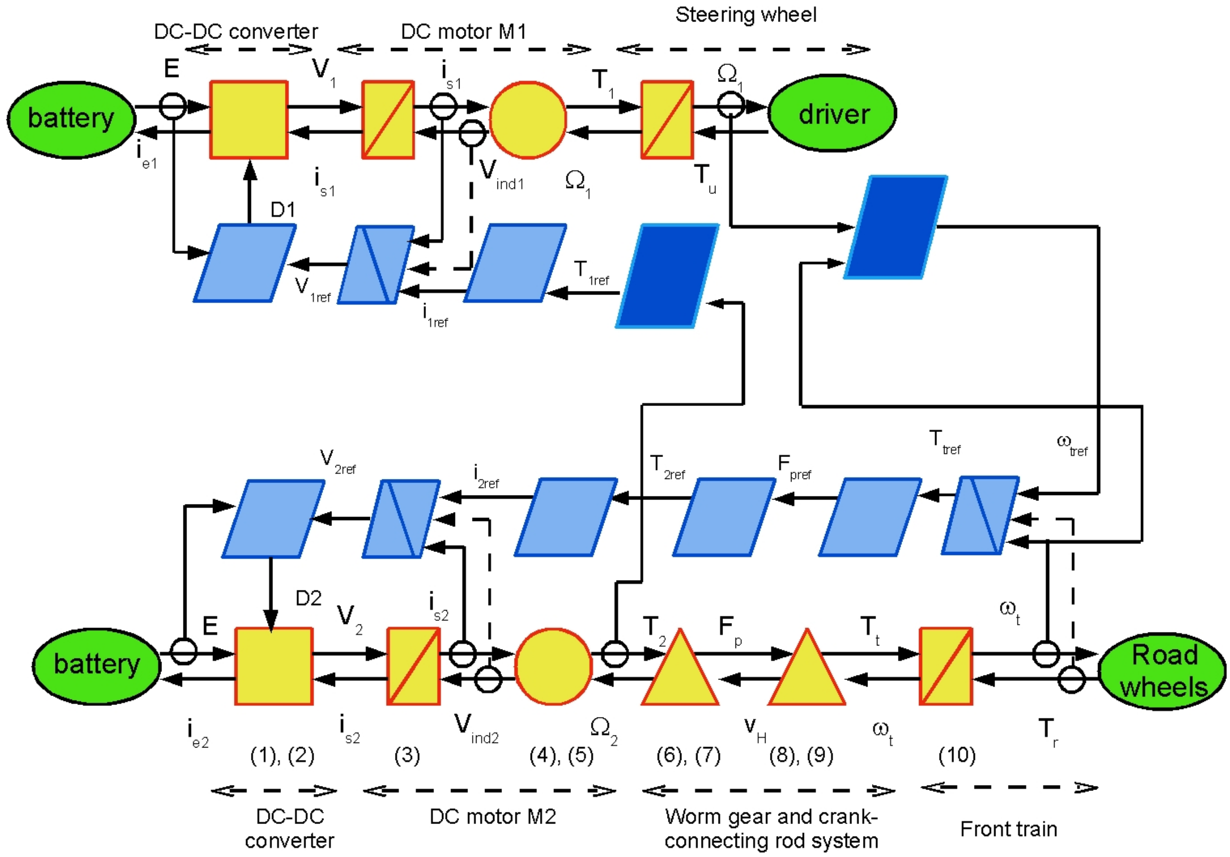

Fig. 4. EMR of the system.

D. Inversion Based Control

The students have first to describe the constraint of their control, and which variable have to be regulated. In the case of the steer-by-wire system, they have to control the output torque of the motor $M1$, and the angular position θ_2 of the front train tires. They have to limit the flowing current in each motor, and the maximum revolving speed of $M1$ and $M2$.

In order to deduce their control scheme, they also write down the tuning chains. The tuning chains follow the action line of the system: students start from the variable to be regulated, and they try to find an exit to the system. For example, in the case of the motor $M1$, the tuning chain, from the output torque T_1 is:

$$T_1 \leftarrow i_{s1} \leftarrow V_1 \leftarrow D_1$$

In fact, E is not a variable which is controlled. This operation helps student to understand the interactions inside the system. The tuning chain of $M2$ is:

$$\theta_2 \leftarrow \omega_t \leftarrow T_t \leftarrow F_p \leftarrow T_2 \leftarrow i_{s2} \leftarrow V_2 \leftarrow D_2$$

The two subsystems' controllers are then deduced by inverting each element of the tuning chain step by step: the controller is presented in blue in figure 4. It appears that students have to prototype one current controller for $M1$, and two controllers for $M2$ (one current controller, and one position controller). They also discuss the amount of required measurements and sensors to achieve their design. For example, compensation of V_{ind1} should be included in the current controller. But how to measure V_{ind1}? Students may propose estimation methods or evaluate performances of the loop controller without compensation. This point is not detailed in this paper, and we suppose that every measurement is possible.

E. cross couplings

In a steer-by-wire system, the rotational angle of the front train is given by the rotational position of the steering wheel, while the output torque of the steering-wheel is a function of the torque on $M2$. By this way, driver has a force feedback, which improves his agility. This feedback is achieved by introducing two parameters names k_1 and k_2, such as:

$$T_{1ref} = k_1 T_2 \quad (11)$$

$$\theta_{2ref} = k_2 \int \Omega_1 dt \quad (12)$$

This is a control strategy, which has to differ from other relationship in the modelling. This is why they are colored into dark blue in the EMR.

F. Simulation

Students simulate each subsystem independently to check the validity of the equations. Moreover, they also check their controllers, beginning by the internal loop: they always check that reference is equal to the variable and prove that the two subsystems are stable independently.

The input to the system is a torque applied by the user to the steering wheel (T_u): the user turns left, stays in that position and then turns right. The environment is simulated as a soft spring, and we programmed $T_r = K_e \theta_2$. The results are presented in figure 5.

At the top of this figure, we have presented the position of the road wheel, as a function of time, and its reference: both curves are close, showing a good control of the road wheels' position. In the $(\theta_1;\theta_2)$ plane, the the curve is a straight line, because the relationship between these two variables is given by equation 12. Also in figure 5, we

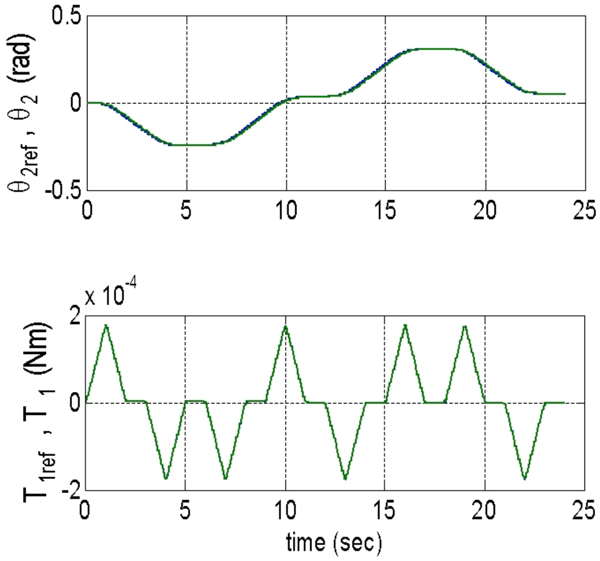

Fig. 5. System's behavior; top side: position of the road wheels, bottom side: force feedback on the steering wheel.

presented the force feedback on the steering wheel: at the bottom side of this figure, we have shown T_{1ref} and T_1 to show that the output torque $M1$ is well controlled. The force feedback operation, because in the $(T_r;T_1)$ plane, the operation of the system describes a line, as what is expressed by equation 11.

At the end of the simulation session, students simulate a stiffer road behaviour, which can be the case when the road wheels are stopped by an obstacle. In figure 7, K_e rises up with a step function: before $t = 0$, K_e is small, but for $t > 0$, K_e rises up suddenly. As it can be seen, the stiff behaviour make the system becoming unstable, and results in oscillations of the steering wheel, and the road wheels. These oscillations are due to the cross couplings between the two subsystems, and occur even if both subsystems are stable independently. How to control this systems avoiding oscillations is outside the scope of the paper; one may refer to [11] to find solutions. But it is interesting to show students the limitations of their control.

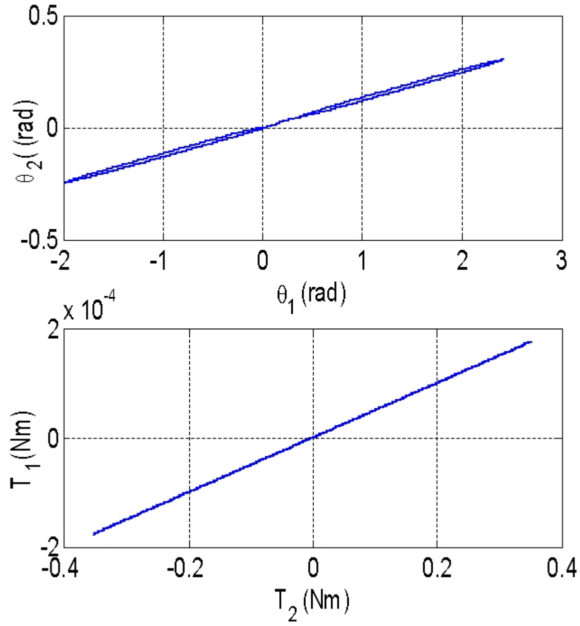

Fig. 6. Couplings of the two subsystems

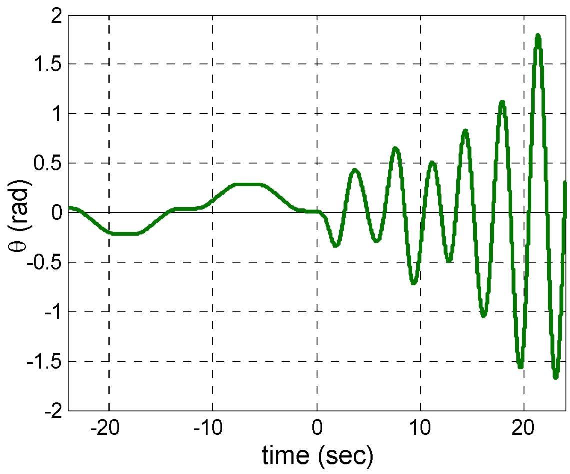

Fig. 7. System's behavior when a stiff obstacle is presented at t=0.

V. Conclusion

The use of EMR is an efficient methodology to develop student skills on drive control. A unified and physical modelling is developed, and inversion rules are used to find the control scheme. By using this intermediary step, the students can easily connect other scientific fields such as power electronics, electrical machines, mechanics and automatic control. In the expert level, complex systems are studied to develop scientific skills on drive control. Evaluations of the unit have shown a very good acquisition of fundamentals on drive control. In this paper, an example of a steer-by-wire system is presented. Despite the complexity of the control, the students are able to define systematically the control scheme and to achieve good simulation results for analysis and discussion.

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