Different models of a traction drive for An electric vehicle simulation

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***Abstract*— Various simulations of Electric Vehicles (EVs) or Hybrid Electric Vehicles (HEVs) are achieved for different objectives. In this paper, the influence of the electrical drive model is studied for simulation of an EV. Indeed, the electric machine with its associated converter can be modelled in three different ways: dynamic, static and quasi-static modelling. The studied electric machine is an induction machine. The aims of this paper are to show different effects of each model on an EV simulation and to study when each model should be used.**

Keywords- Electic drive, Hybrid Electric Vehicle, Model, Simulation

I. Introduction

New vehicles have to be developed to take up the challenge of the reduction of green house gazes and the future oil shortage. EVs and HEVs seem to be promising solutions. During different phases of the development of this type of vehicle, simulation is a key issue, which requires modelling of different components. Indeed, Simulation allows testing different vehicles and the vehicle in different situations. The type of model depends on the objectives of simulation. This paper is in the same philosophy than a previous work on the importance of the clutch in the simulation of a HEV [1].

This paper is focused on the modelling of an electric drive (electric machine and its associated power electronics and its control). So, instead of modelling a HEV with its entire component a simple EV will be used to test different models of the electric drive. EV can be classified by the propulsion traction systems: one motor or two wheel motor topologies [3], [5]. The studied vehicle is a full electric vehicle with one electric traction drive. It is composed of an electric machine which is linked to the front differential via a fixed ratio gear box (*Fig. 1*).

The objective of this paper is to compare each model of the electric drive on different points of view (e.g. dynamic performance, energy consumption…). Another interest is to determine when a dynamic model of the electric drive is required or when a static or a quasi-static model is sufficient for a simulation of an EV. To model each electrical drive Energetic Macroscopic Representation (EMR) is used [1]. EMR is a graphical description tool which allows highlighting the energy flow in a system and to control the system by an inversion based principle.

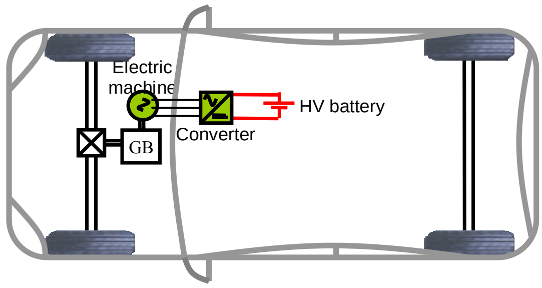

Fig. 1: Studied vehicle

II. Different ways to model an Electric drive

The different models of the studied electric drive are presented. The first studied model is the dynamic model. A static model is then introduced. Finally, the compromise between both models is studied: the quasi-static model. EMR is used to represent the modelling of the electric vehicle with the different models. EMR has been developed to propose a new graphical representation able of highlighting the energy flow in electromechanical systems. Since it is based on the integral causality it is also possible to systematically deduce a control scheme. EMR is a graphical description, which respect three principles.

Interaction principle — The system is decomposed into basic subsystems in interactions (see Appendix): energy sources (green ovals pictograms), accumulation elements with energy accumulation (orange rectangles pictograms), conversion elements without energy accumulation (various orange pictograms) and coupling elements for energy distribution (orange overlapped pictograms). All elements are interconnected according to the action and reaction principle using exchange variables. The product of the action and reaction variables between two elements leads to the instantaneous power exchanged.

Causality principle — Only the integral causality, i.e. the physical causality, is considered in EMR. This property leads to define accumulation elements by time-dependant relationships between their variables, in which outputs are integral functions of inputs. Other elements are described using relationships without time dependence. In order to respect the integral causality specific association rules have been defined [6].

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***Control principle* —** Different steps are required to deduce the control structure from the EMR of the system. Firstly, the tuning path of the system is defined. The tuning paths link the tuning inputs to act on the system to the outputs to control. Then, these tuning paths are inverted step-by-step using the inversion rules. The inversion-based control theory has been initiated by COG (Causal Ordering Graph) [7]. In this methodology, relationships without time-dependence are directly inverted (with neither controller nor measurement). Because the derivative causality is not allowed, a direct inversion of time-dependence relationships is not possible. An indirect inversion is thus done using a controller and possible measurements. These inversion rules have been extended to EMR (blue pictograms): conversion elements are directly inverted and accumulation elements are inverted using controllers. Moreover inversions of coupling elements either require distribution or weighting inputs. These inputs lead to organize the distribution of energy. This inversion methodology is another way to locate controllers and measurements (or estimations). At this stage, all variables are considered measurable. Then, simplifications and estimations of non-measured variables are achieved (this step is not realized in this paper).

A. Global model and control of the studied vehicle

1) Global model of the studied vehicle

***Electric drive* —**A first EMR (orange part) is developed for an EV by using generic model of the electric machine and its converter (circle Fig. 2). This pictogram can represent the dynamic, quasi-static or static model of the electric drive. The details of each model are explained in the part II.B and II.C. The studied electric machine is an induction machine. Mechanical brakes are neglected in this study.

***Battery* —** The battery (oval) delivers the DC voltage v_{bat} to supply the converters, which produce a current i_{conv}.

Gearbox — The reduction gear torque T_{gb} and its rotation speed Ω_{gb} are obtained from the electric machine torque T_{em} and the rotation speed of the wheel Ω_w:

$$\begin{cases} T_{gb} = k_{gb}\ T_{em} \\ \Omega_{gb} = k_{gb}\ \Omega_w \end{cases} \tag{1}$$

where k_{gb} is the fixed gear ratio of the gearbox with the assumption of no losses.

***Wheels* —** The slip phenomenon of the wheels is neglected and all inertias are merged with the vehicle mass. The traction force, F_w, is obtained from the gearbox torque and the wheel rotation speeds from the velocity v_{hev} using the wheel radius R_{wh}:

$$\begin{cases} F_w = k\ T_{gb} \\ \Omega_w = k\ v_{veh} \end{cases} \quad \text{with} \quad k = \frac{1}{R_{wh}} \tag{2}$$

The rotation speeds of each wheel are identical due to the assumption of straight lines. But, in this way, the model can be extended to take curves into account.

***Chassis* —** The chassis couple the traction forces produced by each wheel (not presented in Fig. 2). Moreover the chassis accumulates kinetic energy in the mass of the vehicle (crossed rectangle).

The vehicle velocity v_{veh} is the state variable of this accumulation element (rectangle with an oblique bar), derived from the total traction force F_w and the resistant force F_{res}:

$$M_{equ} \frac{d}{dt} v_{veh} = F_w - F_{res} \tag{3}$$

Environment — This mechanical source yields the resistant force F_{res} mainly composed of drag, friction and slope components.

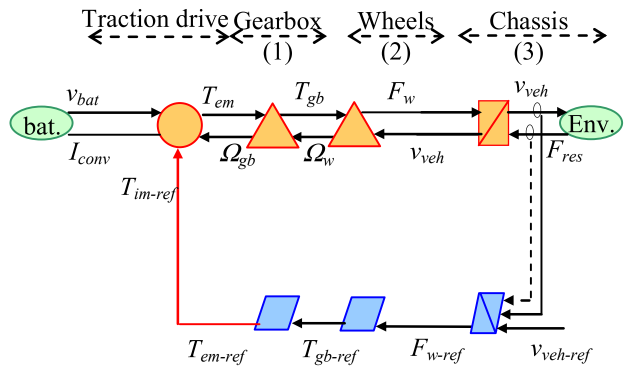

Fig. 2: EMR and control structure of studied vehicle with a generic model of the electric machine

2) Global control of the studied vehicle

An inversion-based control is deduced from this EMR (blue part Fig. 2).

***Tuning path* —** The tuning path links the tuning inputs $T_{em\text{-}ref}$ to the output to control $v_{veh.}$

$$\begin{array}{c} T_{em} \longrightarrow T_{gb} \longrightarrow F_w \longrightarrow v_{veh} \\ \uparrow \\ T_{em\text{-}ref} \end{array}$$

Fig. 3: Tuning chain of the studied vehicle

Inversion of the chassis — This inversion represents the driver in fact. The first element to invert is an accumulation element (3). It requires a controller to define the reference force $F_{w\text{-}ref}$ from the velocity reference $v_{veh\text{-}ref}$, using a rejection of the disturbance F_{res}:

$$F_{tot-ref} = C(t)(v_{veh-ref} - v_{veh-mes}) + F_{res-mes} \tag{4}$$

where *C(t) is* the controller.

Inversion of the wheels and the gearbox — These elements can be directly inverted. The reference torque $T_{im\text{-}ref}$ is deduced from the inversion of (1) and (2):

$$T_{gb-ref} = R_w F_{w-ref} \tag{5}$$

$$T_{em-ref} = \frac{1}{k_{gb}} T_{gb-ref} \tag{6}$$

B. *Dynamic model of the traction drive*

The dynamic model [11] of the electric machine uses a Park-Concordia transformation (Fig. 4). In this model the inverter of the induction machine is also modelled. This system is controlled using modulations ratios of the inverter.

The induction machine is model using a classical (d, q) dynamic modelling. First, the Park-Concordia transformation expresses stator voltages ($\underline{U}$) and current (i_1, i_2) in the park frame (7):

$$\begin{cases} v_{sd-q} = [T(\theta)]u \\ i_{1,2} = [T'(\theta)]i_{sd-q} \end{cases} \tag{7}$$

where θ is the rotor flux position.

In the Park-Concordia frame, the stator winding imposes the stator currents ($\underline{i}_{sd-q}$) using the stator voltages ($\underline{u}_{sd-q}$) and the e.m.f. ($\underline{e}_{sd-q}$) (8).

$$L_s \frac{d}{dt}\underline{i}_{sd-q} = \underline{u}_{sd-q} - \underline{e}_{sd-q} - R_s\,\underline{i}_{sd-q} \tag{8}$$

where R_s is the resistance of the stator winding and L_s is the cyclic inductance of the stator windings.

The electromechanical conversion (double circle Fig. 4) yields the e.m.f. and the induction machine torque (T_{im}) from the current and the rotation speed (9):

$$\begin{cases} T_{em} = k_1 \Phi_{rd} . i_{sq} \\ \underline{e}_{sd-q} = f(\underline{i}_{sd-q}, \theta, \Phi_{rd}) \end{cases} \tag{9}$$

The rotor flux Φ_{rd} is given by equation (10):

$$k_2 \frac{d}{dt}\Phi_{rd} = k_3\, i_{sd} + \Phi_{rd} \tag{10}$$

Where k_i, are combinations of machine parameters.

An EMR can be deduce from this modelling and a field oriented control can be obtained by an inversion of this EMR [6] (Fig. 4)

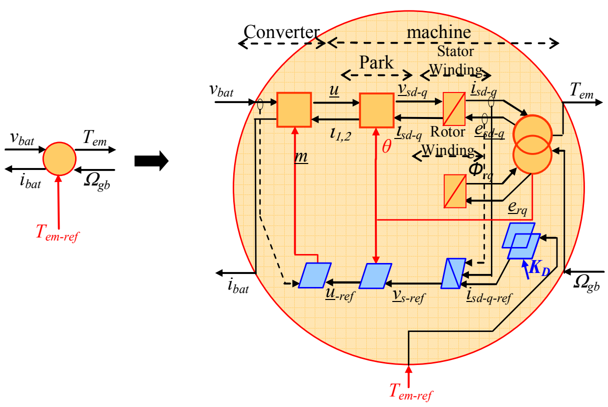

Fig.4: Representation of an induction machine, its converter and its control using EMR

C. *Static model of a traction drive*

The second studied model is the static model [8] (Fig. 5). In this model there is no time constant. This model takes into account the inverter, the induction machine and its control. Indeed, the electric machine is directly controlled by a reference torque, contrarily to the previous model. That means that this model is not only composed of the inverter and the electric machine but all the local control is also included. So, it presumes that the local control is well done.

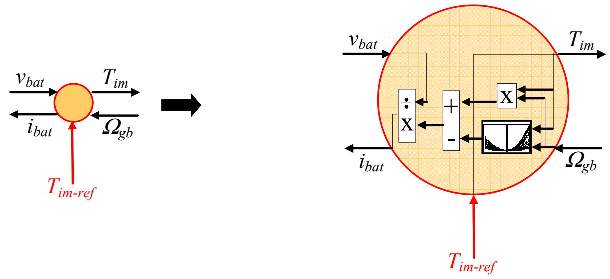

Fig.5: Representation of static model of an induction machine, its converter and its control using EMR

The torque is equal to the reference torque and the current is model by (11)

$$i_{bat} = \frac{(T_{em}.\Omega_{gb}) - P_{losses}}{v_{bat}} \tag{11}$$

where P_{losses} is found with a map which depends on the torque (T_{im}) and the speed (Ω_{gb}).

This map is done using the dynamic simulation of this electric drive (copper losses are neglected in this map). On this map a freedom degree is given on the precision: the step size of the torque and of the speed (e.g. Fig.6 shows the efficiency map with a torque step size of T_{step}=10 Nm and a speed step size of Ω_{step}=100 rad/s).

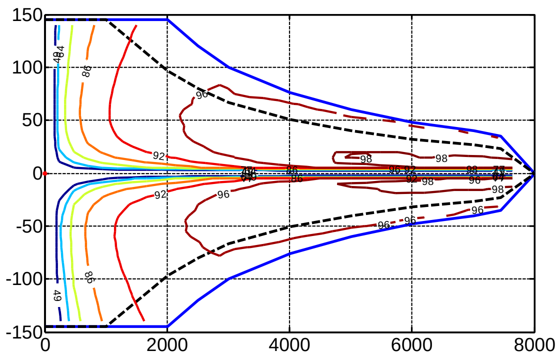

Fig.6: Efficiency map of the electric drive done from the dynamic simulation

D. *Quasi-static model of a traction drive*

The quasi-static model is a compromise between the dynamic model and the static model. Indeed, this model is the same model than the static model but it has the main time constant which represent the time response of the electric drive in closed loop (Fig. 7).

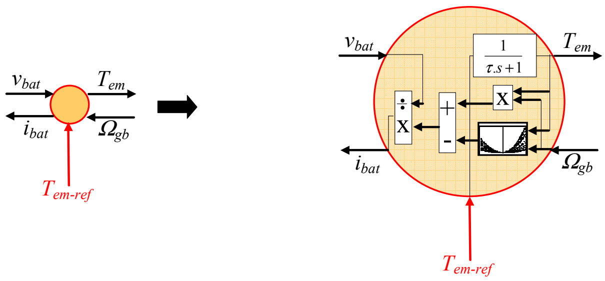

Fig.7: Representation of quasi-static of an induction machine, its converter and its control using EMR

The question of the use of a first or second order filter to characterize the response time of the electric drive is often asked.

Indeed, it should be noted that the response of the dynamic model (in green in Fig. 8) is closed to look like a second order than a first order but the use of a IP controller in the dynamic model permit to avoid this similarity (in blue in Fig. 8). So, a simple first order filter seems to be sufficient [9].

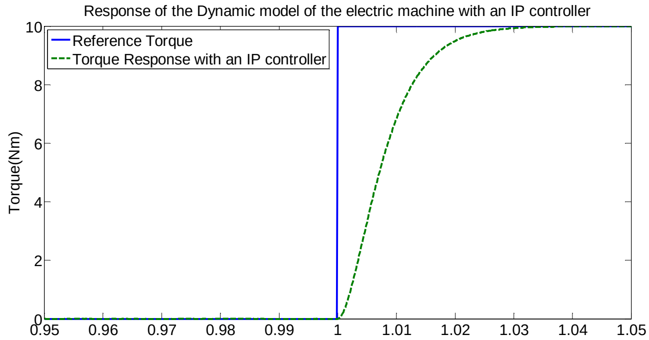

Fig.8: Torque response of the dynamic model of the electric machine with different controllers

III. Comparison between the different models

Each model can be directly transposed into MATLAB-Simulink© (Fig. 9, Fig. 10) using the EMR Library.

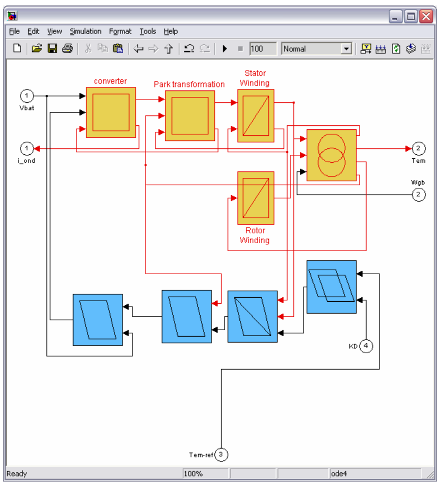

Fig. 9: Simulation model in Matlab-Simulink© of the dynamic model of the electric drive

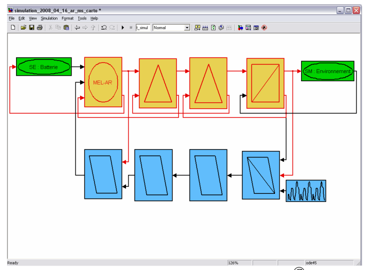

Fig. 10: Simulation model in Matlab-Simulink© with a generic model of the electric machine

The Models have been compared during an ECE-15 urban cycle (195 s). These comparisons have been done in different aspects: the simulation time, the dynamics of the vehicle (i.e. drive ability) and the energy consumption [10].

A. *Simulation time*

The first comparison between models is about the simulation time (Table 1). The static and the quasi-static model simulation time are closed to each other. But the difference with the dynamic model is really important, 30% less than the dynamic model.

Table 1: Simulation time of each model

Model	Time of simulation (t_{final}=195 s)
Dynamic	18.198 s
Quasi-static	11.642 s
Static	10.377 s

B. *Dynamics of the vehicle*

The following comparison is done by comparing dynamic aspect. In other word this first comparison consists of comparing the response of the system to a reference. It is shown (Fig. 11) that models are really closed to each other. But the quasi-static model is closer to the dynamic model. The difference between both is less than 1%.

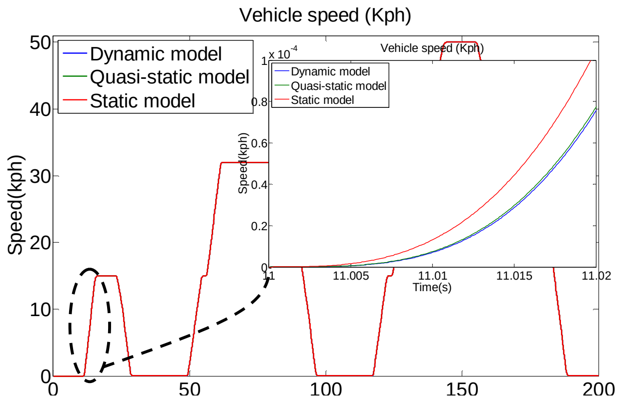

Fig. 11: dynamic performances simulation results

C. *Losses and energy consumption*

The next comparison is done by comparing the losses of the induction machine. Losses are found using (12).

$$P_{losses} = P_{elec} - P_{mec} = v_{bat}.i_{conv} - T_{em}.\Omega_{gb} \qquad (12)$$

Fig. 12 shows the losses of each model. The losses in the electric drive are quite the same on each model (difference less than 1%). So, if the objective of a simulation is to study the electrical consumption and the efficiency of an EV, a static model seems to be sufficient.

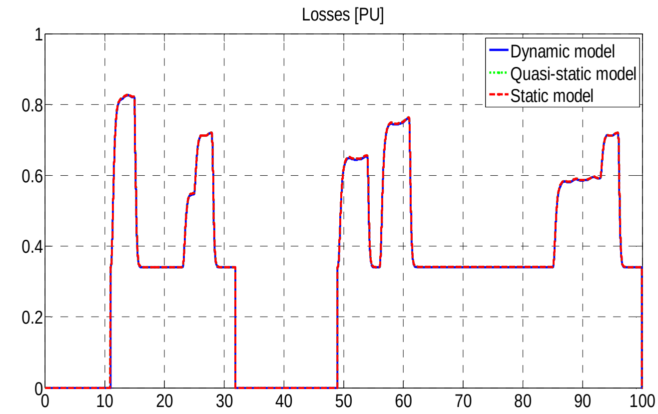

Fig. 12: Losses in the induction machine

A study is done to compare the difference between the losses in a dynamic model and a static model by changing the precision of the efficiency map. Fig. 13 shows that the losses difference is very dependant on the precision of the losses table. Indeed, with a high precision losses table the difference between static and dynamic model is lower than 1%, contrary to a low precision table where the difference between static and dynamic model goes up to 7%.

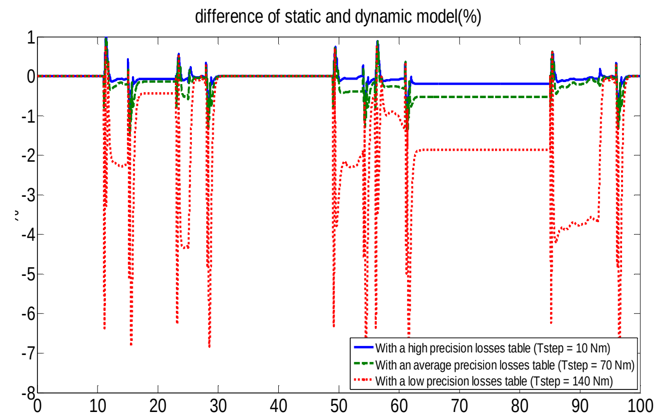

Fig. 13: Difference of losses between static and dynamic model with different precision of the losses table

For a better understanding Fig. 14 shows the Energy lost difference for three different torque step size. It shows that when the losses table has a high precision (Blue in Fig. 14), the difference between models are neglected, contrary to the one with the low precision table (red dotted line in Fig. 14).

This study shows that for having a suitable result a high precision losses table is needed. So, it rises up the problem of the making of an enough precise losses table.

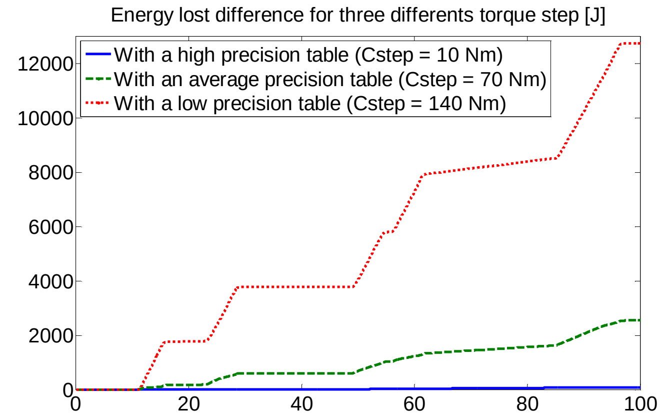

Fig. 14: Average error versus the torque step size

To summarize the advantages and drawbacks between each model and when each model can be used a table is done (Table 2).

Table 2: Summarize of the advantages and drawbacks of each model

	Dynamic model	Quasi-static model	Static model
Advantages	- Show transient and steady state with accuracy, - possible to use the deduced control in the real time	-Take into account the dynamic of the electric drive, - simulation time.	- Simulation time.
Drawbacks	- Simulation time, - modelling complexity.	- Modelling simplicity, - need a high precision losses table.	- No dynamic is taken into account - modelling simplicity, - Need a high precision losses table
Use	- HIL Simulation, - transient state study, - Control design.	- Study of power and energy during steady and transient state.	- Study of power and energy during steady states (e.g. global optimisation).

IV. Conclusion

Different models of an induction machine were shown. This step has shown that the quasi-static model and the static model are not only composed of the model, but they are composed of the close control of the induction machine.

The second step of this paper has shown the difference between models and when we can use each model. It can be remark that in a Hardware In the Loop simulation a dynamic model must be used. This argument is definitely accepted in University application but most of the times, in a car manufacturer application, they have not access to the converter. Indeed, the electric machine is combined with its power electronic so the control is done by giving torque. It supposes that the closer control is good and so a static or a quasi-static model can be sufficient. If the goal is to do an efficiency study a static model with a good losses table seems to be sufficient. The drawback which is shown there is that the efficiency of the quasi-static or of the static model is really dependant on the precision of the losses table.

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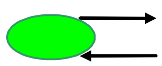
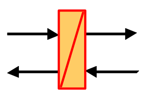
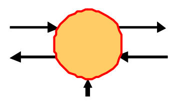
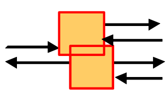
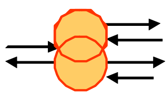
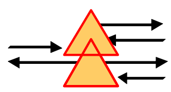
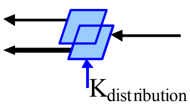
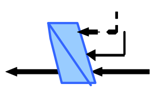
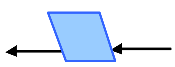
APPENDIX: SYNOPTIC OF ENERGETIC MACROSCOPIC REPRESENTATION (EMR)

	Source of energy		Element with energy accumulation		Electro-mechanical converter (without energy accumulation)
	Electrical coupling device (energy distribution)		Electro-mechanical coupling device (energy distribution)		Mechanical coupling device (energy distribution)
 $K_{distribution}$	Coupling inversion bloc		Control block With controller		Control block without controller