Inversion-based control of electromechanical systems using causal graphical descriptions

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Abstract—Causal Ordering Graph and Energetic Macroscopic Representation are graphical descriptions to model electromechanical systems using integral causality. Inversion rules have been defined in order to deduce control structure step-by-step from these graphical descriptions. These two modeling tools can be used together to develop a two-layer control of system with complex parts. A double-drive paper system is taken as an example. The deduced control yields good performances of tension regulation and velocity tracking.

I. INTRODUCTION

Causal Ordering Graph (COG) has been introduced ten years ago [1][2] to describe power electronics and electrical machines for developing their control. This graphical description uses integral causality to organize a causal graph of variables. The inversion of this graph yields the control structure of the system with measurements and controllers.

Energetic Macroscopic Representation (EMR) has been introduced in 2000 to describe complex electromechanical drives, especially multi-drives systems [3]. EMR is based on action reaction principle, which organizes the system as interconnected sub-systems according to the integral causality. An inversion of this description leads to macro-control blocs.

In this paper, Causal Ordering Graph and Energetic Macroscopic Representation are coupled for a double-layer control of complex electromechanical drives. A double-drive paper system is chosen as an example. The global control of the system is deduced from EMR and the local velocity control of the band tension is deduced from the COG according to Hook’s law. Simulation results highlight the interest of this double-layer control for increasing dynamics of actual systems without complex and advanced control methods.

II. CAUSALITY AND GRAPHICAL DESCRIPTION

A. Causal modeling

A System is composed of inputs and outputs. Its modeling consists in expressing outputs from inputs.

Electromechanical systems can be decomposed into elementary interconnected elements, which manage energy: dissipation, storage and transformation. All sub-systems can be modeled using differential equations with state variables. These variables are associated with energy and are dependent on inputs and time according to integral causality [1][4][5]. When inputs change, the state variables reach other steady states after transient states: outputs are always consequence of inputs.

The natural causality is the integral causality because it respects the energy flowing considering the state variables as delayed from their inputs. Integral causal modeling leads then to a more physical description. Derivative causality is sometimes used in simulation because it avoids expressing all elements according to the integral causality. Some association problems in complex systems are thus solved [6]. But derivative causality yields a longer computation time.

B. Causal Ordering Graph (COG)

The causal ordering graph is a graphical description based on the integral causality [1][2]. On the contrary of Bond-Graph [6], COG doesn’t authorize the derivative causality.

Two kinds of relationships are considered: rigid relationships without any time dependence between output and input. That means that an input change instantaneously leads to an output change. There is no delay. A rigid relationship is depicted by an orange balloon involving a double arrow inside: output and input cannot be permutated and there is a delay between them. For example, the Ohm’s law connects a current $i_R$ and a voltage $u_R$ through a rigid relationship using the resistance $R$ (Fig. 1a):

$$u_R = R i_R \text{ or } i_R = \frac{1}{R} u_R$$  

(C1)

Causal relationships are associated with time-dependence equations. According to the integral causality, the output is mandatory an integration of the input. This kind of relationship is depicted by orange balloons with a single arrow inside: output and input cannot be permutated and there is a delay between them. For example, the inductor relationship links the voltage $u_L$ and the current $i_L$ through a causal relationship using the inductance $L$ (Fig. 1b):

$$\frac{d}{dt}i_L = \frac{1}{L} u_L \text{ or } i_L = \frac{1}{L} \int u_L dt + i_L(0)$$  

(C2)

All linear elements can be depicted using these two kinds of relationships connected by their inputs and outputs.

Fig. 1: COG with rigid (a) and causal (b) relationships
REFERENCES


APPENDIX: SYNOPTIC OF COG AND EMR

<table>
<thead>
<tr>
<th>u</th>
<th>y</th>
<th>Relationship without time dependence</th>
<th>Source of energy</th>
<th>Element with energy accumulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>t</td>
<td>y</td>
<td>Direct inversion</td>
<td>Electrical converter (without energy accumulation)</td>
<td>Control block without controller</td>
</tr>
<tr>
<td>t_{tan}</td>
<td>y_{ref}</td>
<td>Relationship with an integral causality</td>
<td>Mechanical converter (without energy accumulation)</td>
<td>Control block with controller</td>
</tr>
<tr>
<td>y_{tan}</td>
<td>y_{ref}</td>
<td>Indirect inversion using controller</td>
<td>Electromechanical converter (without energy accumulation)</td>
<td>Control block with controller</td>
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