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Model inversion of electrical engineering systems from bicausal bond graphs

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Abstract – In this paper, the application of bicausal bond graphs for model inversion of typical electrical engineering systems is emphasised. Inverse models are particularly useful for the synthesis step of the system design process. To illustrate these issues, a typical railway traction device and an Aeronautic Electro Hydrostatic Actuator are considered as case studies. From the requirements applied to the system outputs, we show how the synthesis of electrical constraints can be carried out from the inverse bicausal Bond Graph.

Keywords: b ond gr aph, bicausal ity, mo del inversion, electrical engineering, synthesis.

I. INTRODUCTION

Electrical en gineering sy stems ar e more an d more complex and heterogeneous, b eing constituted by elements of different varieties strongly coupled in different ph ysical f ields. With in this f ramework, th e system a nalysis b ecomes complicated so that a un ified formalism such as the Bond Graph (BG) [Paynter, 1961; Karnopp & al., 2000; Dauphin-Tanguy, 2000] is particularly useful. H omogeneous modelling and causality based sy stem an alysis methods directly applicable on bond graphs are the major in terest of this formalism [Sueur and Dauphin-Tanguy, 1991a; Sueur and Dauphin-Tanguy, 1991b; Louca and Stein, 1999; Gandanegara & al., 2001; Gandanegara & al., 2003].

Having chose n system architecture and parameter sizing, the system an alysis process consists in ve rifying if the device fulfils the requirements: this is usually done from a system's model and its simulation. An it erative process consisting in verifying allocations (choices of structure and/or parameters) from digital simulations is usually applied. T his itera tive process, in volving th e control st rategy even f rom th e first des ign st eps, is sometimes long and tiresome.

On the contrary, the synthesis process consists in choosing t he sy stem s tructure and its s izing, dir ectly starting from the requirements. This "inverse process" is essential for the design of complex energetic systems and is complementary to the analysis process. On bo nd gr aph fo rmalism, t he properties of bicausality can help to solve the issue of model inversion [Gawthrop, 1995; Ngwompo & al., 1996; Ngwompo, 1997; Ngwompo and Gawthrop, 1999; Ngwompo and Scavarda, 1999; Gawthrop, 2000]. This paper aims a t show ing how bond graph fo rmalism associated with the bicausal a pproach can be useful to construct in verse models th at can then be used to manage system design issues.

Two typical case studies are considered:

- a r ailway traction dev ice composed of an electromechanical assoc iation in cluding a power source, a DC-DC converter feeding a DC machine which dr ives the electromechanical tr ansmission line,
- an Electro Hydrostatic Actuator (EHA) for the position con trol o f flight control surfaces in aeronautic applications.

The principles and c haracteristics of bicausality are discussed in sec tion II. The model in version with the invertibility condition is described in section III. The modelling (dir ect an d in verse) of the railway traction device an d the EHA is ill ustrated in the next sections. Validation and simulation r esults are also presented for the model inversion.

II. BASIC CHARACTERISTICS OF BICAUSALITY

Contrarily to the classical causality in bond graphs, the causal stroke can be divided in 2 causal half strokes: one f or the flow variable (f) and on e for the effort t variable (e). Thus, we can examine the assignment on the model by applying this type of causality, which is called bicausality.

The concept o f bicausality was in vented an d f irst published by P.J. Gawthrop [Gawthrop, 1995]. This proposition h as open ed a n ew research f ield in bo nd graph applications [Ngwompo & al., 1996; Ngwompo, 1997; Ngwompo and Gawthrop, 1999; Ngwompo and Scavarda, 1999; Gawthrop, 2000] for:

- *system inversion*: if the BG s tructure, th e parameters and the initial states are chosen, and if

outputs a re given f rom sy stem requi rements, th e necessary inputs can be directly defined from a bicausal solver;

- state estimation: if parameters, inputs and outputs are give n, dy namic e lements in itial states can be deduced; In this paper, the state estimation is not studied. So, we will consider that the initial states of dynamic elements are known;
- parameter estimation: if inputs, outputs, initial states are given and if a set of parameters are fixed, the other parameters values can be synthesised. The number of parameters that can be determined depends on the degrees of freedom in t he system (number of provided inputs/outputs).

In bicausal bond graphs, the causality of each variable is separ ately examined. With causal h alf strokes, there are 4 possibilities. The conventional o r ph ysical causality presented in Fig. 1 is a particular case of the bicausality where both causal half strokes are placed on the same side o f bond. The others are represented on Fig. 2. Note that, if the conventional causality gives considerable information a bout the physical meaning of associations, the bicausality is purely conceptual and is consequently only useful for the design process.

Graphical convention: the flow information is on the bond side with a half arrow (in our examples, it is below the bond).

The assign ment of the bicausality on bo nd gra ph elements for r1 inear cases is ill ustrated in [Ngwompo, 1997]. Note that by using the bicausality, parameter values can be deduced in relation to the effort and f low information. Ho wever, there are also some inadmissible cases because of insufficient information (see Fig. 3.a) or redundant information (see Fig. 3.b).

Note: in bicausal BGs, it is preferred to replace the notation Sf, Se, De and Df by SS (source – se nsor elements) even if their causality is not changed (both causal half strokes are on the same side of the bond). In this case, these SS elements are called the effort source – flow sensor (for Se and Df) or the flow source – effort sensor (for Sf and De).

III. THE MODEL INVERSION PROCESS

An inverse model can only be obtained if the direct model is in vertible. Therefore, it is necessary to firstly test this property on the bond graph before applying the bicausality inversion process. For this purpose, several definitions are employed [Ngwompo, 1997].

Definition 1: Two s ingle Input /single Output (I/O) causal paths are disjoint if they do not pass th rough any common variable (effort or flow).





A imposes its effort on B whose consequence is its flow $e_B := e_A$

 $f_A := f_B$

B imposes its effort on A whose consequence is its flow

$$e_A \coloneqq e_B$$
$$f_B \coloneqq f_A$$

Fig. 1. Causality assignments.



A imposes its effort and flow on B $e_B := e_A$ $f_B := f_A$



$$f_{A}\coloneqq f_{\mathrm{B}}$$

Fig. 2. Bicausality assignments.



(a). Only R is known, it is impossible to deduce e and f.

(b). $r = \frac{e_1}{f_2}$ and $r = \frac{e_2}{f_1}$ (redundant information).

Fig. 3. Examples of inadmissible cases in bicausality.

- **Definition 2:** A set S is disjo int if it consists of m disjoint I/O causal paths.
- **Definition 3:** The order $\omega_p(u_i, y_i)$ of an I/O causal path p between an input u_i and an output y_i is defined as:

$$\boldsymbol{\omega}_{p}(\boldsymbol{u}_{i},\boldsymbol{y}_{i}) = \boldsymbol{n}_{I}(\boldsymbol{p}) - \boldsymbol{n}_{D}(\boldsymbol{p}) \tag{1}$$

where $n_I(p)$ (respectively $n_D(p)$) is the number of dynamic elements in in tegral (r espectively differential) causality crossed by this causal path.

Definition 4: The order $\omega(S)$ of a set S of m disjoint I/O causal paths p_{i} , i = 1 to m, is :

$$\omega(S) = \sum_{i=1}^{m} \omega_{p_i}$$
(2)

By using these definitions on the direct b ond graph, the invertibility condition for a MIMO model with minputs and m outputs is:

- If there is n o choice for the set of *m* disjoint I/O causal pa ths, t he mo del is structurally not invertible.
- If there is on ly one choice for the set of *m* disjoint I/O causal paths, the model is structur ally invertible.
- If there are several choices, we should apply the Modified Sequential Causality Procedure for Inversion (MSCAPI) [Ngwompo & al., 1996; Ngwompo, 1997].

- Determine a set S_0 whose order is the smallest (cf. Definition 4).
- Replace all so urces and detectors associated with the c ontrol v ariables or i nputs and outputs by SS elements.
- Assign effort source flow source causality to the SS o utput elements and propagate the causal in formation t o the SS in put elements. This propagation has to arrive and impose effort detector – flow detector causality on input SS elements. Oth er elements take the causality due to the bicausality propagation and junction conventions. These conventions are:
 - § For 1–junctions:
 - effort side: o nly one bond without half stroke near the junction,
 - flow side: on ly one bond without half stroke near the junction.
 - § For 0–junctions:
 - effort side: only one bond with half stroke close to the junction,
 - flow side: only one bond with h alf stroke close to the junction.
- If there is a tl east a c ausality conflict, the model is not invertible. In the other case, it is invertible.

When the model is invertible, the following procedure can be applied to c onstruct the inverse model (or the synthesis model) using b icausality [Ngwompo & al., 1996]:

- 1. Replace all so urce and detector elements by *SS* elements.
- 2. In relation to the degrees of freedom, apply the bicausality effort source flow source on the output

elements an d effort sen sor - flow sensor on t he input elements or o n th e elements w hose parameters have to be synthesised.

3. Propagate the b icausality from o utputs to inputs. Other elements take the causality due to the bicausality propagation with r espect to junction conventions.

The obtained bond graph is then called *a bicausal bond graph*.

IV. APPLICATION ON A RAILWAY TRACTION DEVICE

In order to apply these methods, a r ailway traction system is firstly considered. Basically, the model of this device is a "simpl ified vision" of the traction part of a locomotive [Lochot & al., 1997]. The considered structure is composed of a Direct Current voltage source, an RLC in put filter conn ected to a DC-DC chopper feeding a Dir ect Cur rent ma chine which d rives the mechanical transmission line. It h as been mode lled in bond graph (see Fig. 4) and several analyses have been carried o ut in recent p ublications [Gan danegara & al., 2001; Gandanegara, 2003; Gandanegara & al., 2003] as model sim plification or stability analysis. To test the device behaviour with real conditions, the Central Business District (CBD) cycle has been retained as the system dr iving mi ssion [CBD_w eb]. The CDB cycle is considered as a reference for the design of traction sy stems. E ach cy cle includes a velocity acceleration phase, a constant velocity phase at 20 mph, a velocity deceleration (or braking) phase and a phase with z ero velocity. T he curves of velocity and power source applied to our case study are illustrated in Fig. 5. It can be seen t hat n egative powers (i.e. regen erative phase) are obtained.



Fig. 4. Direct causal bond graph of a railway traction device with an equivalent DC motor.



Fig. 5. CBD cycles: (a) velocity and (b) power source curves.

In the direct causal bond graph, the DC voltage source (U_{cont}) , the duty cycle α of the DC–DC converter and the resistive force (F_{res}) can be considered as the inputs and the obtained source current and velocity as the outputs. In particular, we are only interested on the duty cycle as the controlled input and the velocity as the output. Let us consider the I/O causal paths L_i from the control variable α to the flow variable (train velocity) at the bond 42 f_{42} (see Fig. 4): there are 4 choices of I/O causal paths, where X indicates that the BG element X is crossed by the causal path.

R Second choice:
$$\omega_2(\alpha, f_{42}) = 11$$

 $L_2 = \alpha - e_7 - e_9 - \boxed{L_{DC}} - f_9 - f_{10} - e_{11} - e_{12} - \boxed{I_6}$
 $-f_{12} - f_{13} - f_{14} - f_{16} - \boxed{C_{acc}} - e_{16} - e_{14} - e_{17}$
 $-e_{18} - \boxed{I_5} - f_{18} - f_{19} - f_{20} - f_{21} - \boxed{K_4} - e_{21} - e_{16}$

$$\begin{array}{c} e_{22} - e_{23} - e_{24} - \boxed{I_4} - f_{24} - f_{25} - f_{26} - f_{27} - \boxed{K_5} \\ - e_{27} - e_{28} - e_{29} - e_{30} - \boxed{I_3} - f_{30} - f_{31} - f_{32} - f_{33} - \boxed{K_{jac}} - e_{33} - e_{32} - e_{35} - e_{36} - \boxed{I_9} - f_{36} - f_{37} - f_{38} - \boxed{K_{ess}} - e_{38} - e_{39} - e_{40} - \boxed{I_{eq}} - f_{40} - f_{41} - f_{42}. \end{array}$$

- R Third choice: $\omega_3(\alpha, f_{42}) = 11$
 - $L_{3} = \alpha e_{7} e_{9} \underline{L_{DC}} f_{9} f_{10} e_{11} e_{12} \underline{I_{6}} \\ -f_{12} f_{13} f_{14} f_{15} \underline{K_{acc}} e_{15} e_{14} e_{17} \\ -e_{18} \underline{I_{5}} f_{18} f_{19} f_{20} f_{21} \underline{K_{4}} e_{21} e_{22} e_{23} e_{24} \underline{I_{4}} f_{24} f_{25} f_{26} f_{27} \underline{K_{5}} \\ -e_{27} e_{28} e_{29} e_{30} \underline{I_{3}} f_{30} f_{31} f_{32} f_{33} \underline{C_{jac}} e_{33} e_{32} e_{35} e_{36} \underline{I_{9}} f_{36} f_{37} f_{38} \underline{K_{ess}} e_{38} e_{39} e_{40} \underline{I_{eq}} f_{40} f_{41} f_{42}.$
- R Fourth choice: $\omega_4(\alpha, f_{42}) = 10$
 - $L_{4} = \alpha e_{7} e_{9} \underline{L_{DC}} f_{9} f_{10} e_{11} e_{12} \underline{I_{6}} \\ -f_{12} f_{13} f_{14} f_{15} \underline{C_{acc}} e_{15} e_{14} e_{17} \\ -e_{18} \underline{I_{5}} f_{18} f_{19} f_{20} f_{21} \underline{K_{4}} e_{21} \\ e_{22} e_{23} e_{24} \underline{I_{4}} f_{24} f_{25} f_{26} f_{27} \underline{K_{5}} \\ -e_{27} e_{28} e_{29} e_{30} \underline{I_{3}} f_{30} f_{31} f_{32} \\ f_{33} \underline{C_{jac}} e_{33} e_{32} e_{35} e_{36} \underline{I_{9}} f_{36} \\ f_{37} f_{38} \underline{K_{ess}} e_{38} e_{39} e_{40} \underline{I_{ea}} f_{40} \\ f_{41} f_{42}.$

Given that several choices of I/O c ausal path s exist, we can not directly deduce if the model is in vertible or not. In this case, the MSCAPI proce dure has to be applied. The last choice is associated with the I/O causal path with the small est or der. In this way, we examine this path. After having replaced the input (in this case, the right b ond of the MTF_{α}) by an effort sen sor – flow sensor and the output (the detector *Velocity*) by an effort source – flow source *SS* e lement w ith e = 0, the bicausality propagation does not imply any causality conflicts (see Fig. 6). Therefore, the model is in vertible. The model o btained by the MSCAPI procedure is also the inverse model. In this in verse model, the resistive force and the velocity information r elated to the CBD cycles are injected.

Note that by considering the driving mission (CBD cycles) as requirements, the electrical constraints can "directly" be synthesised by means of this bicausal approach from the model inversion. This example emphasizes the design capacity of this methodology in electrical engineering in the context of a "top down" systemic approach.

Simulations ar e car ried out by means of the 20 Sim software. A modified li brary of this solver h as been developed by the LEEI in order to take bicausality in account. Note that the inversed model is implicit (many *I* and *C* elements are in derivative causality), so that we use the *Backward Differentiation Formula* (BDF) as an integration method.



Fig. 6. Inverse model to obtain the duty cycle α .



Fig. 7. Comparison between direct model and inverse model responses: duty cycle α .

The train speed (f_{42} on Fig. 4) required by the CBD cycle (see Fig. 5.a) is obtained with the direct BG model by means of a speed control. The resistive force (F_{res}) is also obtained thanks to the CBD power cy cle (see Fig. 5.b). As a vali dation of the inversion process, these two variables (F_{res} and f_{42}) given by the direct BG are used as the inputs of the inverse model (respectively e_{44} and f_{43} of the Fig. 6). The Fig. 7 shows the dut y cycle obtained from the inverse model compared with the one obtained from the direct model. No te that the direct BG should i nclude th e c ontrol str ategy, c ontrarily to the inverse model. This result proves that the inverse model is validated.

Finally, the inverse BG model allows us to synthesise the electr ical constraints on the system (see Fig. 8). These results are particularly useful in order to design

the electrical p art (i.e. pow er electronic devices) in the context of electronic technologies.





Fig. 8. Synthesis by model inversion of the loading current f_6 (a) and the capacitor voltage e_6 (b) from CBD cycles.

In numerous devices such as the one considered here as a case study, the loading power is very time variable (see here the CBD cycle of Fig. 5) so that the peak power is f ar from the average power consumed. For such systems, the main source must be "over-dimensioned" to take in to acc ount the maximum peak power deman d which presents a gr eat dr awback f rom the economic point of view. The general idea in hybrid systems is well known for relectr ical v ehicles but it al so becomes applicable in oth er fields. For r ailway traction systems, hybridisation can offer advantages such as a reduction of energy consumption and of pollution (carbon emissions) when diesel-electric devices are used.

In hybrid systems, it is necessary to associate the main energy source with a sto rage device, suc h as supercapacitors, batt eries of accumulators, or in ertia wheels. With such co mponents, th e primary energy source will o nly have to furnish the average loading power and the average system losses. The variations of the consumed power can be provided by the storage element(s).

The bicausality can also be used in order to size the storage element of such hybrid system as illustrated on Fig. 9, in the particular case of a supercacitor (C_{store}). On this bicausal BG:

- Step 1: the loading current (I_{load}) can be obtained thanks to the previous bicausal sy nthesis (see Fig. 8.a);
- Step 2: t he desired voltage and current (SS: U_{cont}) are forced to satisfy the requirements: the source current i s ob tained by means of a Lo w Pass Filtering (LPF) of the loading current.

V. THE MODEL INVERSION OF AN ELECTRO HYDROSTATIC ACTUATOR

A second case study can be considered to illustrate the capacity of the bicausal ap proach. We consider h ere a bond gr aph modelli ng of an E lectro Hydrostatic Actuator (E HA) dedicat ed to the position c ontrol of flight control sur faces in Airbus air crafts. A more detailed an d accura te des cription of the Bond Graph model is proposed in [Langlois & al., 2005]. The synoptic and a sim plified vision of the A320 BG model are given in Fig. 10. In this model, the permanent magnet sy nchronous motor actually used in EHAs is replaced by an energetically equivalent DC moto r. This latter is connected with a DC- DC c hopper f ed by an ideal vo ltage source. T he electrical motor drives a hydraulic pump which sets the position of the hydraulic jack. Consequently, the position control of the flight control sur face can be obtained. Following the plane

speed, the altitude and the position of the flight control surface, a consequent aerodynamic effort is applied.

Airbus is able to specify typical cy cles for t he aerodynamic e fforts and f or the positions of the flight control surface. A tim e derivative of these positions gives th e v alues of the flight c ontrol surface rotation speed. The issue is then t o inverse the BG model to synthesise the subsequent electrical constraints (voltage, current, electrical power).

The inverse BG model is given on the Fig. 11: the new inputs (aerodynamic effort, sur face rotation speed) are directly applied on the *SS* element in the inverse model. The subsequent outputs are the load current and the duty cycle or the motor voltage.

In order to validate the model inversion, the outputs of the direct B G (aerodynamic effort, sur face rotation speed) a re applied as the in puts of the inverse model. The motor cur rent and the duty cycle obtained form the inverse model are compared (see Fig. 12) with the ones given by the direct BG. The perfect accordance between both models validates the inversion process by means of the BDF solver of 20 Sim.

Finally, the requirements corresponding to an a ctual flight cy cle ar e affected to the inputs (aerodynamic effort, surface rotation speed) of the inverse BG. The corresponding outputs (i.e. the electrical constraints) are obtained and shown on the Fig. 13. These kinds of information are particularly useful during the system design p rocess. Indeed, following the requirements of the entire system (here a flight control surface EHA) and a set of the given device parameters (motor, pump, jack, surface inertia), t he obtained electrical requi rements allow to specify the power e lectronic or the power source. In this case, i t can be seen that, due to the filtering effect of the dynamic elements of this system, the maxi mum peak on the electrical power is greater $(\times 2.86)$ than the one obtained at the system output (i.e. the aerodynamic power).



Fig. 9. Bicausal BG for the synthesis of a storage element.



(b)

Fig. 10. EHA: (a) synoptic and (b) simplified causal BG.



Fig. 11. Inverse bicausal BG model of the EHA.



Fig. 12. Validation of the inversion process for a position step on the flight control surface



Fig. 13. Bicausal synthesis of electrical constraints from an actual flight cycle.

VI. CONCLUSION

In this paper, the application of the bicausal approach for the system design in el ectrical engineering has been emphasised. This "synthetic approach" has been applied and validated on typical electrical engineering devices: a railway traction system and an E lectro Hydrostatic Actuator for the flight control of aircrafts.

The capacity of the bicausality for model inversion has been put forward. By considering a given dr iving mission as the requirements, the in put constraints can "directly" be synthesised by means of this b icausal approach, contrarily to the classical "analytical approach" which usual ly requires the control strategy setting as well as several it eration cy cles between allocations (design choices) and analysis (allocation verification).

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