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: bond graph, bicausality, model inversion, electrical engineering, synthesis.

I. Introduction

Electrical engineering systems are more and more complex and heterogeneous, being constituted by elements of different varieties strongly coupled in different physical fields. With in this framework, the system analysis becomes complicated so that a unified formalism such as the Bond Graph (BG) [Paynter, 1961; Karnopp & al., 2000; Dauphin-Tanguy, 2000] is particularly useful. Homogeneous modelling and causality based system analysis methods directly applicable on bond graphs are the major interest of this formalism [Sueur and Dauphin-Tanguy, 1991a; Sueur and Dauphin-Tanguy, 1991b; Louca and Stein, 1999; Gandanegara & al., 2001; Gandanegara & al., 2003].

Having chosen system architecture and parameter sizing, the system analysis process consists in verifying if the device fulfils the requirements: this is usually done from a system's model and its simulation. An iterative process consisting in verifying allocations (choices of structure and/or parameters) from digital simulations is usually applied. This iterative process, involving the control strategy even from the first design steps, is sometimes long and tiresome.

On the contrary, the synthesis process consists in choosing the system structure and its sizing, directly starting from the requirements. This "inverse process" is essential for the design of complex energetic systems and is complementary to the analysis process.

On bond graph formalism, the 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 at showing how bond graph formalism associated with the bicausal approach can be useful to construct inverse models that can then be used to manage system design issues.

Two typical case studies are considered:

– a railway traction device composed of an electromechanical association including a power source, a DC–DC converter feeding a DC machine which drives the electromechanical transmission line,
– an Electro Hydrostatic Actuator (EHA) for the position control of flight control surfaces in aeronautic applications.

The principles and characteristics of bicausality are discussed in section II. The model inversion with the invertibility condition is described in section III. The modelling (direct and inverse) of the railway traction device and the EHA is illustrated in the next sections. Validation and simulation results 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 for the flow variable (*f*) and one for the effort variable (*e*). Thus, we can examine the assignment on the model by applying this type of causality, which is called bicausality.

The concept of bicausality was invented and first published by P.J. Gawthrop [Gawthrop, 1995]. This proposition has opened a new research field in bond graph applications [Ngwompo & al., 1996; Ngwompo, 1997; Ngwompo and Gawthrop, 1999; Ngwompo and Scavarda, 1999; Gawthrop, 2000] for:

– *system inversion*: if the BG structure, the parameters and the initial states are chosen, and if outputs are given from system requirements, the necessary inputs can be directly defined from a bicausal solver;

– *state estimation*: if parameters, inputs and outputs are given, dynamic elements initial 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 the system (number of provided inputs/outputs).

In bicausal bond graphs, the causality of each variable is separately examined. With causal half strokes, there are 4 possibilities. The conventional or physical causality presented in Fig. 1 is a particular case of the bicausality where both causal half strokes are placed on the same side of bond. The others are represented on Fig. 2. Note that, if the conventional causality gives considerable information about 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).

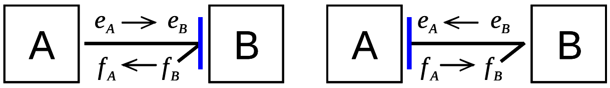
The assignment of the bicausality on bond graph elements for linear cases is illustrated in [Ngwompo, 1997]. Note that by using the bicausality, parameter values can be deduced in relation to the effort and flow information. However, there are also some inadmissible cases because of insufficient information (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 – sensor 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 invertible. 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 single Input /single Output (I/O) causal paths are disjoint if they do not pass through any common variable (effort or flow).



A imposes its effort on B whose consequence is its flow

$e_B := e_A$

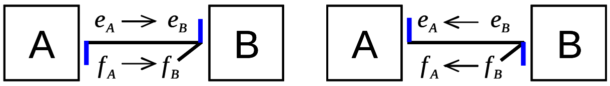
$f_A := f_B$

B imposes its effort on A whose consequence is its flow

$e_A := e_B$

$f_B := f_A$

Fig. 1. Causality assignments.



A imposes its effort and flow on B

$e_B := e_A$

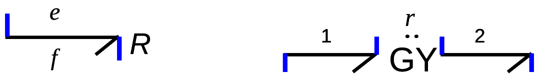
$f_B := f_A$

B imposes its effort and flow on A

$e_A := e_B$

$f_A := f_B$

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 disjoint 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:

$$\omega_p(u_i, y_i) = n_I(p) - n_D(p) \qquad (1)$$

where $n_I(p)$ (respectively $n_D(p)$) is the number of dynamic elements in integral (respectively 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 :

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

By using these definitions on the direct bond graph, the invertibility condition for a MIMO model with *m* inputs and *m* outputs is:

– If there is no choice for the set of *m* disjoint I/O causal paths, the model is structurally not invertible.

– If there is only one choice for the set of *m* disjoint I/O causal paths, the model is structurally 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 sources and detectors associated with the control variables or inputs and outputs by *SS* elements.
- Assign effort source – flow source causality to the *SS* output elements and propagate the causal information to the *SS* input elements. This propagation has to arrive and impose effort detector – flow detector causality on input *SS* elements. Other elements take the causality due to the bicausality propagation and junction conventions. These conventions are:
  - For 1–junctions:
    - effort side: only one bond without half stroke near the junction,
    - flow side: only 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 half stroke close to the junction.
- If there is at least a causality 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 construct the inverse model (or the synthesis model) using bicausality [Ngwompo & al., 1996]:

1. Replace all source 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 and effort sensor – flow sensor on the input elements or on the elements whose parameters have to be synthesised.
3. Propagate the bicausality from outputs to inputs. Other elements take the causality due to the bicausality propagation with respect 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 railway traction system is firstly considered. Basically, the model of this device is a "simplified vision" of the traction part of a locomotive [Lochot & al., 1997]. The considered structure is composed of a Direct Current voltage source, an RLC input filter connected to a DC–DC chopper feeding a Direct Current machine which drives the mechanical transmission line. It has been modelled in bond graph (see Fig. 4) and several analyses have been carried out in recent publications [Gandanegara & al., 2001; Gandanegara, 2003; Gandanegara & al., 2003] as model simplification or stability analysis. To test the device behaviour with real conditions, the *Central Business District* (CBD) cycle has been retained as the system driving mission [CBD_web]. The CDB cycle is considered as a reference for the design of traction systems. Each cycle includes a velocity acceleration phase, a constant velocity phase at 20 mph, a velocity deceleration (or braking) phase and a phase with zero velocity. The curves of velocity and power source applied to our case study are illustrated in Fig. 5. It can be seen that negative powers (i.e. regenerative phase) are obtained.

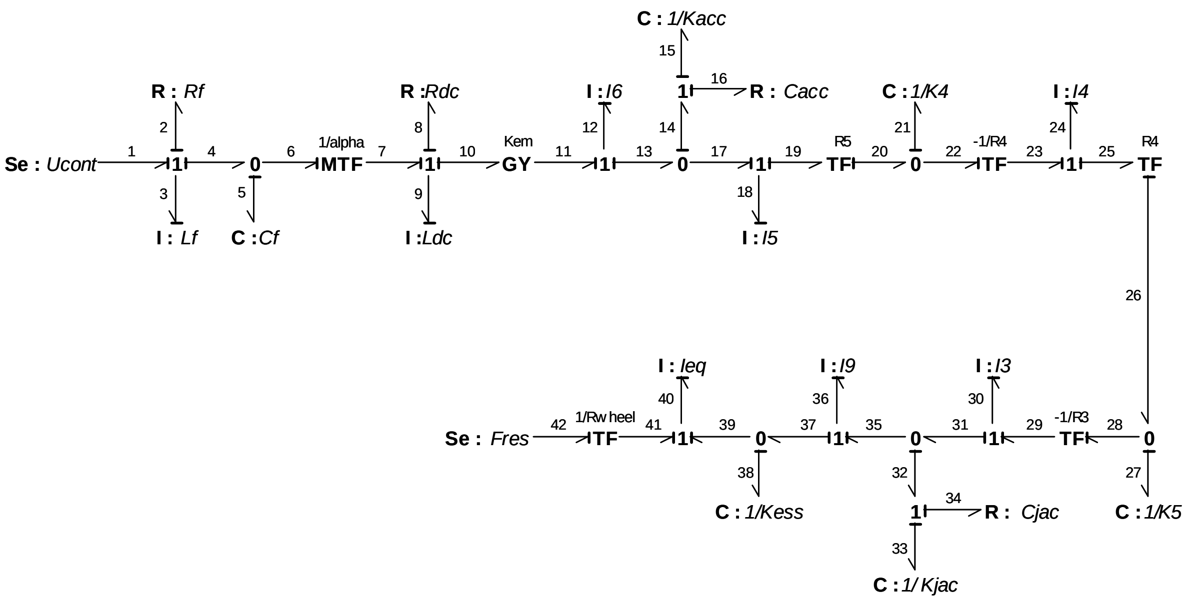
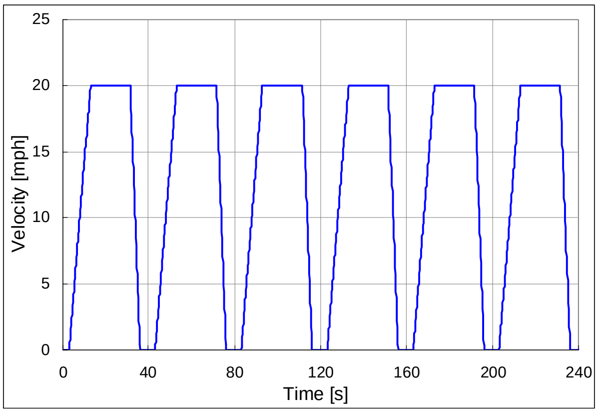
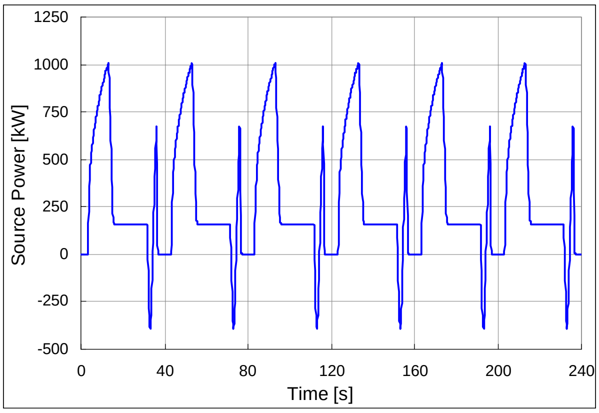


Fig. 4. Direct causal bond graph of a railway traction device with an equivalent DC motor.



(a)



(b)

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 $\boxed{X}$ indicates that the BG element X is crossed by the causal path.

R First choice: $\omega_1(\alpha, f_{42}) = 12$

$$L_1 = \alpha - e_7 - e_9 - \boxed{L_{DC}} - f_9 - f_{10} - e_{11} - e_{12} - \boxed{I_6} - f_{12} - f_{13} - f_{14} - f_{15} - \boxed{K_{acc}} - e_{15} - e_{14} - e_{17} - e_{18} - \boxed{I_5} - f_{18} - f_{19} - f_{20} - f_{21} - \boxed{K_4} - e_{21} - e_{22} - e_{23} - e_{24} - \boxed{I_4} - f_{24} - f_{25} - f_{26} - f_{27} - \boxed{K_5} - e_{27} - e_{28} - e_{29} - e_{30} - \boxed{I_3} - f_{30} - f_{31} - f_{32} - f_{33} - \boxed{K_{jac}} - e_{33} - e_{32} - e_{35} - e_{36} - \boxed{I_9} - f_{36} - f_{37} - f_{38} - \boxed{K_{ess}} - e_{38} - e_{39} - e_{40} - \boxed{I_{eq}} - f_{40} - f_{41} - f_{42}.$$

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

$$L_2 = \alpha - e_7 - e_9 - \boxed{L_{DC}} - f_9 - f_{10} - e_{11} - e_{12} - \boxed{I_6} - f_{12} - f_{13} - f_{14} - f_{16} - \boxed{C_{acc}} - e_{16} - e_{14} - e_{17} - e_{18} - \boxed{I_5} - f_{18} - f_{19} - f_{20} - f_{21} - \boxed{K_4} - e_{21} - e_{22} - e_{23} - e_{24} - \boxed{I_4} - f_{24} - f_{25} - f_{26} - f_{27} - \boxed{K_5} - e_{27} - e_{28} - e_{29} - e_{30} - \boxed{I_3} - f_{30} - f_{31} - f_{32} - f_{33} - \boxed{K_{jac}} - e_{33} - e_{32} - e_{35} - e_{36} - \boxed{I_9} - f_{36} - f_{37} - f_{38} - \boxed{K_{ess}} - e_{38} - e_{39} - e_{40} - \boxed{I_{eq}} - f_{40} - f_{41} - f_{42}.$$

R Third choice: $\omega_3(\alpha, f_{42}) = 11$

$$L_3 = \alpha - e_7 - e_9 - \boxed{L_{DC}} - f_9 - f_{10} - e_{11} - e_{12} - \boxed{I_6} - f_{12} - f_{13} - f_{14} - f_{15} - \boxed{K_{acc}} - e_{15} - e_{14} - e_{17} - e_{18} - \boxed{I_5} - f_{18} - f_{19} - f_{20} - f_{21} - \boxed{K_4} - e_{21} - e_{22} - e_{23} - e_{24} - \boxed{I_4} - f_{24} - f_{25} - f_{26} - f_{27} - \boxed{K_5} - e_{27} - e_{28} - e_{29} - e_{30} - \boxed{I_3} - f_{30} - f_{31} - f_{32} - f_{33} - \boxed{C_{jac}} - e_{33} - e_{32} - e_{35} - e_{36} - \boxed{I_9} - f_{36} - f_{37} - f_{38} - \boxed{K_{ess}} - e_{38} - e_{39} - e_{40} - \boxed{I_{eq}} - f_{40} - f_{41} - f_{42}.$$

R Fourth choice: $\omega_4(\alpha, f_{42}) = 10$

$$L_4 = \alpha - e_7 - e_9 - \boxed{L_{DC}} - f_9 - f_{10} - e_{11} - e_{12} - \boxed{I_6} - f_{12} - f_{13} - f_{14} - f_{15} - \boxed{C_{acc}} - e_{15} - e_{14} - e_{17} - e_{18} - \boxed{I_5} - f_{18} - f_{19} - f_{20} - f_{21} - \boxed{K_4} - e_{21} - e_{22} - e_{23} - e_{24} - \boxed{I_4} - f_{24} - f_{25} - f_{26} - f_{27} - \boxed{K_5} - e_{27} - e_{28} - e_{29} - e_{30} - \boxed{I_3} - f_{30} - f_{31} - f_{32} - f_{33} - \boxed{C_{jac}} - e_{33} - e_{32} - e_{35} - e_{36} - \boxed{I_9} - f_{36} - f_{37} - f_{38} - \boxed{K_{ess}} - e_{38} - e_{39} - e_{40} - \boxed{I_{eq}} - f_{40} - f_{41} - f_{42}.$$

Given that several choices of I/O causal paths exist, we can not directly deduce if the model is invertible or not. In this case, the MSCAPI procedure has to be applied. The last choice is associated with the I/O causal path with the smallest order. In this way, we examine this path. After having replaced the input (in this case, the right bond of the MTF_{α}) by an effort sensor – flow sensor and the output (the detector *Velocity*) by an effort source – flow source *SS* element with $e = 0$, the bicausality propagation does not imply any causality conflicts (see Fig. 6). Therefore, the model is invertible. The model obtained by the MSCAPI procedure is also the inverse model. In this inverse model, the resistive force and the velocity information related 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 are carried out by means of the 20 Sim software. A modified library of this solver has 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.

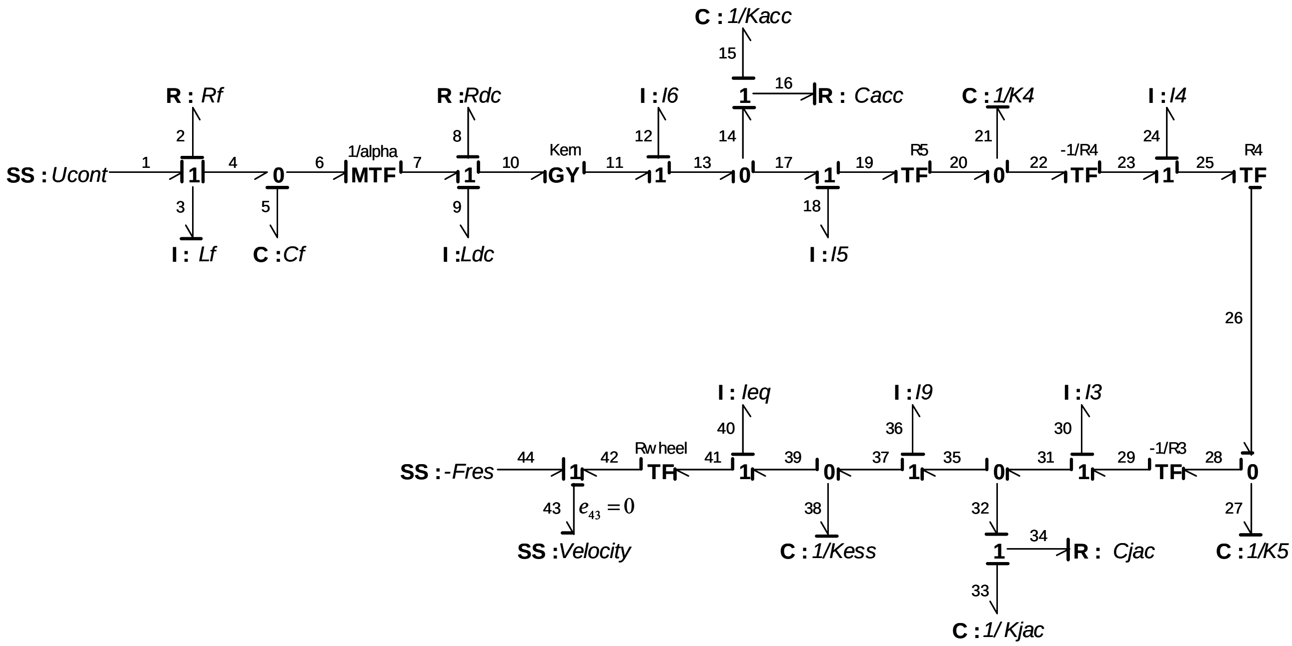


Fig. 6. Inverse model to obtain the duty cycle α.

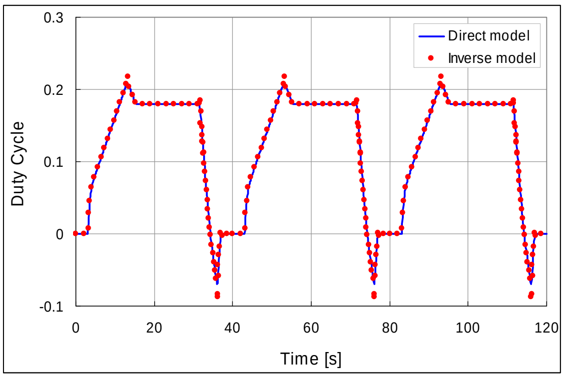
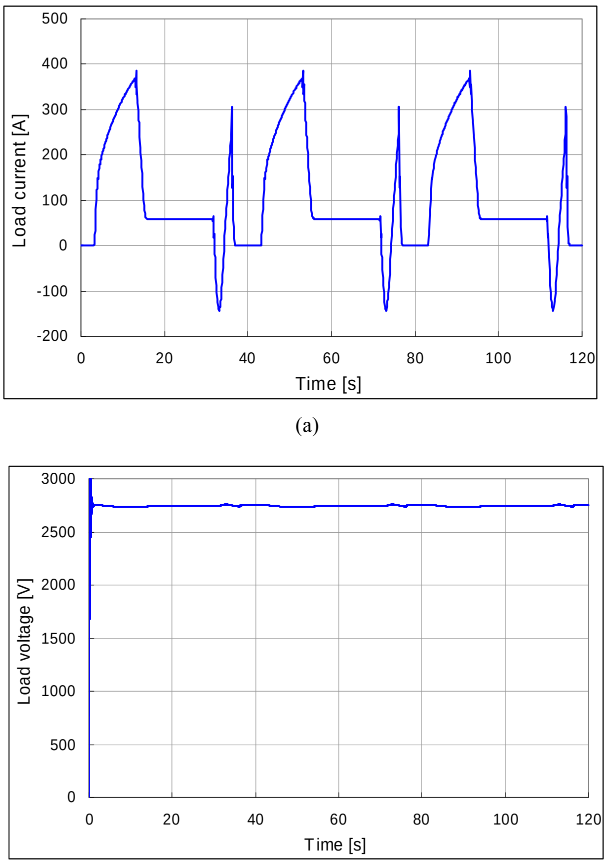


Fig. 7. Comparison between direct model and inverse model responses: duty cycle α.

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 cycle (see Fig. 5.b). As a validation 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 duty cycle obtained from the inverse model compared with the one obtained from the direct model. Note that the direct BG should include the control strategy, contrarily to the inverse model. This result proves that the inverse model is validated.

Finally, the inverse BG model allows us to synthesise the electrical constraints on the system (see Fig. 8). These results are particularly useful in order to design the electrical part (i.e. power electronic devices) in the context of electronic technologies.



(a)

(b)

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 far from the average power consumed. For such systems, the main source must be "over–dimensioned" to take in to account the maximum peak power demand which presents a great drawback from the economic point of view. The general idea in hybrid systems is well known for electrical vehicles but it also becomes applicable in other fields. For railway 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 storage device, such as supercapacitors, batteries of accumulators, or inertia wheels. With such components, the primary energy source will only 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 synthesis (see Fig. 8.a);
– Step 2: the desired voltage and current (*SS*: U_{cont}) are forced to satisfy the requirements: the source current is obtained by means of a Low 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 approach. We consider here a bond graph modelling of an Electro Hydrostatic Actuator (EHA) dedicated to the position control of flight control surfaces in Airbus air crafts. A more detailed and accurate description of the Bond Graph model is proposed in [Langlois & al., 2005]. The synoptic and a simplified vision of the A320 BG model are given in Fig. 10. In this model, the permanent magnet synchronous motor actually used in EHAs is replaced by an energetically equivalent DC motor. This latter is connected with a DC– DC chopper fed by an ideal voltage source. The electrical motor drives a hydraulic pump which sets the position of the hydraulic jack. Consequently, the position control of the flight control surface 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 cycles for the aerodynamic efforts and for the positions of the flight control surface. A time derivative of these positions gives the values of the flight control surface rotation speed. The issue is then to 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, surface 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 BG (aerodynamic effort, surface rotation speed) are applied as the inputs of the inverse model. The motor current 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 actual flight cycle are 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 process. 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), the obtained electrical requirements allow to specify the power electronic or the power source. In this case, it can be seen that, due to the filtering effect of the dynamic elements of this system, the maximum peak on the electrical power is greater (× 2.86) than the one obtained at the system output (i.e. the aerodynamic power).

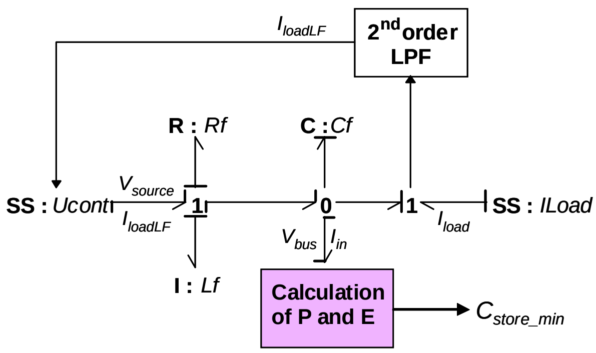
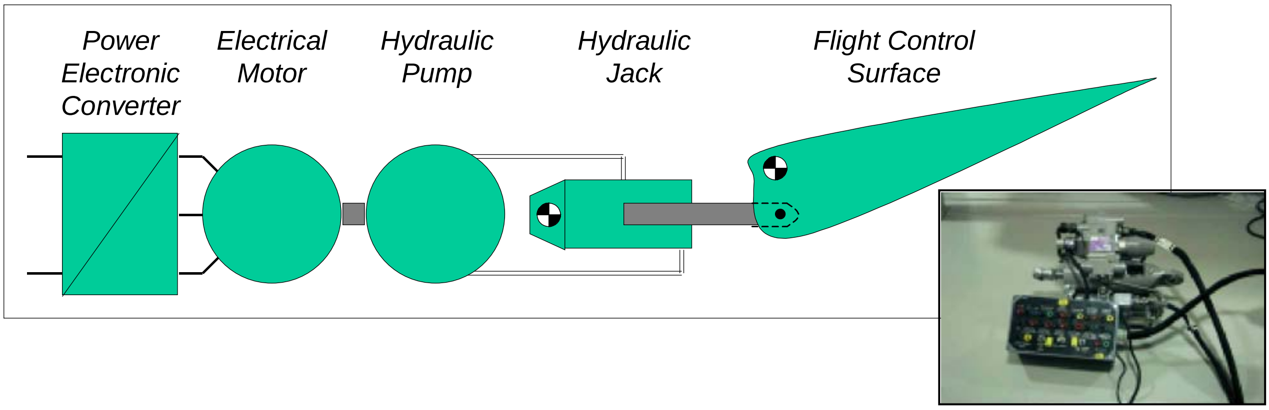
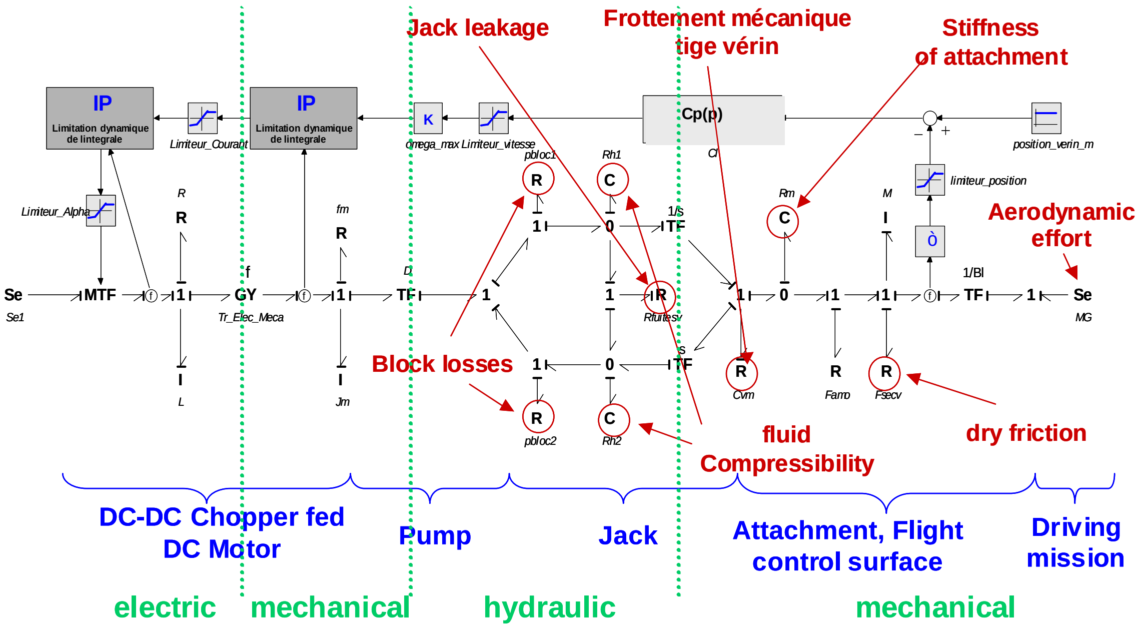


Fig. 9. Bicausal BG for the synthesis of a storage element.



(a)



(b)

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

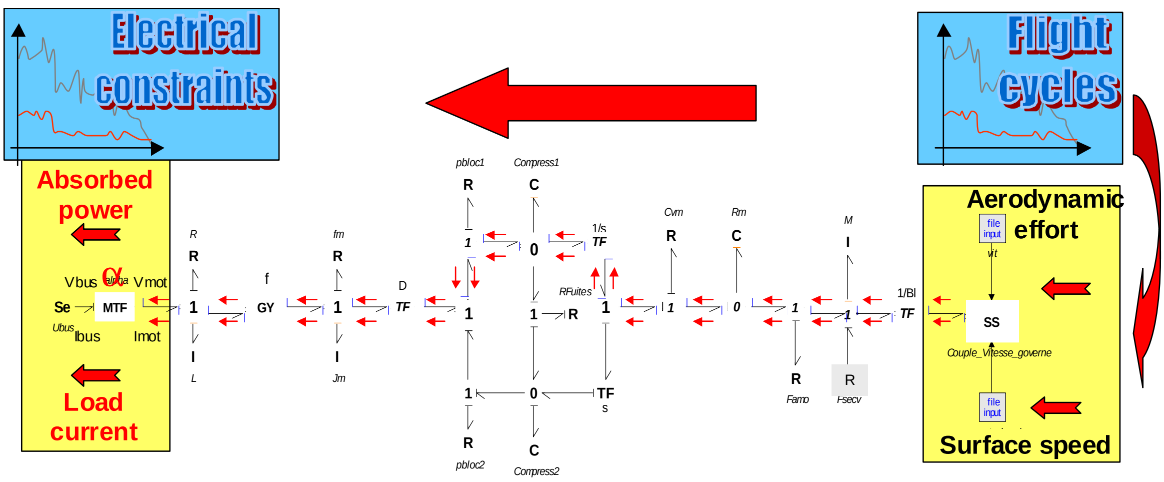


Fig. 11. Inverse bicausal BG model of the EHA.

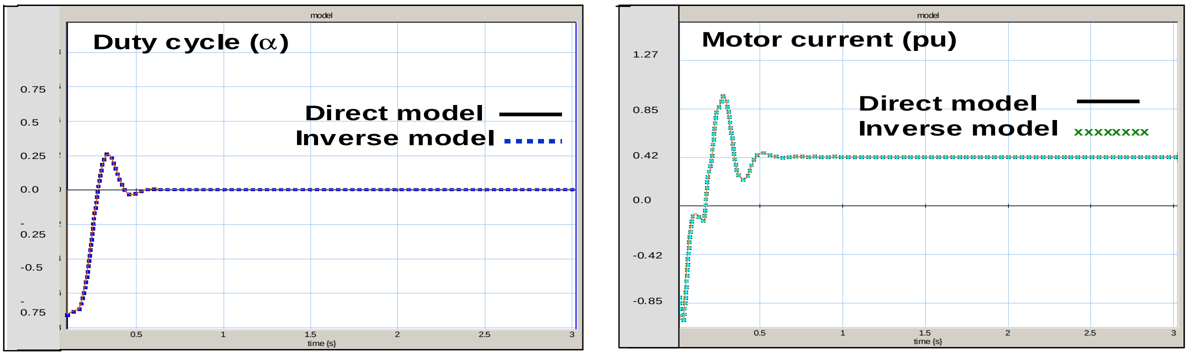


Fig. 12. Validation of the inversion process for a position step on the flight control surface.

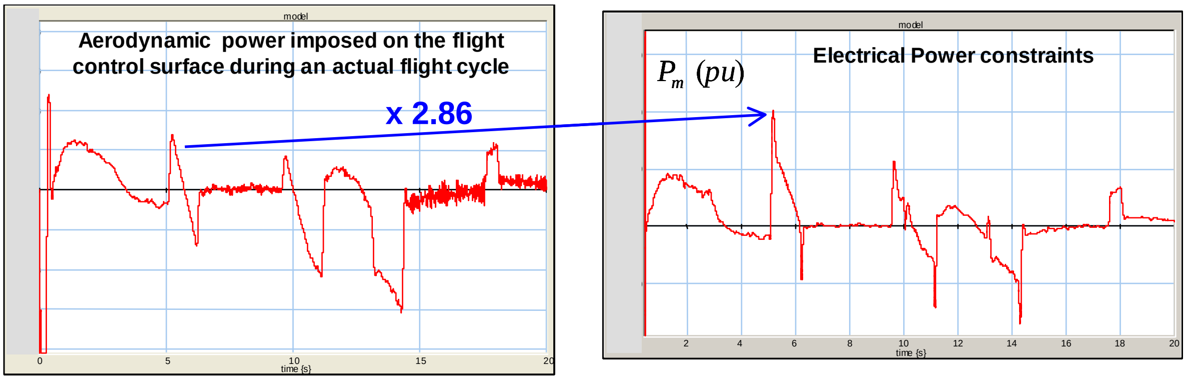


Fig. 13. Bicausal synthesis of electrical constraints from an actual flight cycle.

VI. CONCLUSION

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

The capacity of the bicausality for model inversion has been put forward. By considering a given driving mission as the requirements, the input constraints can "directly" be synthesised by means of this bicausal approach, contrarily to the classical " analytical approach" which usually requires the control strategy setting as well as several iteration cycles between allocations (design choices) and analysis (allocation verification).

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