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Robust Diagnosis of a DC Motor by Bond Graph Approach

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Abstract: In this article, a Bond Graph (BG) approach is used for modeling, simulation and robust diagnosis of a DC Motor. The design and calculation of an observer is achieved by using graphical methods taking advantage of the structural properties of bond graph model. Simulation results are used to show the dynamic behavior of the system variables and assessing the performance of the observer. A modeling Bond Graph form Linear Fractional Transformations (BG-LFT) to generate constituted Analytical Redundant Relationship (ARR) two parts perfectly separated: A nominal portion denotes the residual and an uncertain part, which serves both to the calculation of adaptive thresholds for normal operation and to sensitivity analysis.

Keywords: Bond Graph, Robust Diagnosis, DC Motor, Linear Fractional Transformations, Analytical Redundant Relationship

Introduction

The diagnostic system is primarily intended to issue alarms which aims to draw attention of the supervising operator of the occurrence of one or more events that could affect the proper functioning of the installation.

Given the complexity of the processes, the generation of alarms is the most used way to alert the operator of the occurrence of an "abnormal" event. Alarms are related to malfunctions that may appear on the production system. It is important to clarify the meaning given to the words used to evoke the malfunctions that may occur in the system. We retain, for this, the definitions in (Basseville *et al*., 1987; Anguilar-Martin, 1999; Cassar *et al*., 1994; Graisyhm, 1998; Ploix, 1998; Maquin and Ragot, 2000; Karnopp and Rosenberg, 1983).

These industrial systems are governed by multiple physical phenomena and various technology components, so the Bond Graph approach, based on an energy analysis and multi-physics, is well suited. The Bond Graph modeling tool was defined by Paynter (1961). This approach allows energy to highlight the analogies between the different areas of physics (mechanics, electricity, hydraulics, thermodynamics, acoustics, etc. ...) and represent in a uniform multidisciplinary physical systems (Paynter, 1961; Dauphin-Tanguy, 2000; Ould Bouamama and Dauphin-Tanguy, 2005; Tagina, 1995; Azmani and Dauphin-Tanguy, 1992; Karnopp, 1979; Gawthrop and Smith, 1995; Roberts *et al*., 1995; Rahmani *et al*., 1994; Sueur and Dauphin-Tanguy, 1989; Sueur, 1990). The diagnosis of uncertain systems has been the focus of much research work in recent years (Djeziri, 2007; Djeziri *et al*., 2009). This interest is reflected in the fact that natural systems are complex and non-stationary and manufacturers seek greater safety and efficiency. The Bond Graph approach proposed in this article allows, for its energy structure and multi physics, to use a single tool for modeling, structural analysis and generation of uncertain ARR.

In this study we try to show how the Bond Graph model can be used for modeling, simulation and construction of observers of linear and nonlinear systems (next section) on the one hand and on the other hand the construction of the system elements to be analyzed by bond graph elements as LFT to generate RRAS consist of two parts perfectly separated: A face portion, which is the residue and an uncertain part, which serves both to the calculation of adaptive thresholds for normal operation and sensitivity analysis.

Robust Diagnosis by Bond Graph Approach

Bond Graph Model

Two methods are proposed by Sueur (1990) to build parametric uncertainty by BG. The first is to represent uncertainty on bond graph element as another element of the same type, causally linked to the nominal element (Fig. 1) or the rest of the model. These uncertainties are kept in derivative causality when the model is preferred in integral causality not change the order of the model. The second method is the LFT form (Linear Fractional Transformations) introduced on mathematical models Redheffer (1994).

The physical aspect of the multi-hop graphs comes from the fact that from any physical system, it is possible to obtain an independent graphical representation of the studied physical realm. Building a bond graph model can be done in three levels:

- The technological level
- The physical level
- The structural and mathematical

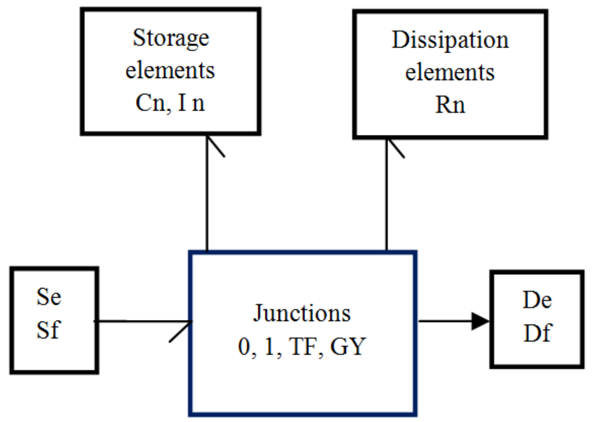

Fig. 1. Representation BG with the nominal element

- Storage elements: potential (C) or inertial (I)
- Dissipation elements: R
- Junction elements: parallel (0), serial (1), transformation and gyrator
- Sources elements: Sources effort or sources flow
- Detectors elements: Detectors effort or detectors flow

LFT Representation

Linear Fractional Transformations (LFTs) are very generic objects used in the modeling of uncertain systems. The universality of LFT is due to the fact that any regular expression can be written in this form after Oustaloup (1994; Alazard *et al*., 1999). This form of representation is used for the synthesis of control laws of uncertain systems using the principle of the μ-analysis. It involves separating the nominal part of a model of its uncertain part as shown in Fig. 2.

Ratings are aggregated into an augmented matrix denoted M, supposedly clean and uncertainties regardless of their type (structured and unstructured parametric uncertainties, modeling uncertainty, measurement noise ...) are combined in a matrix structure Δ diagonal. In the linear case, this standard form leads to a state representation of the form (3):

$$\begin{aligned} \dot{x} &= Ax + B_1 w + B_2 u \\ z &= C_1 x + D_{11} w + D_{12} u \\ y &= C_2 x + D_{21} w + D_{22} u \end{aligned} \tag{1}$$

With:

$x \in R^n$:	System state vector
$u \in R^m$:	Vector grouping system control inputs
$y \in R^p$:	Vector grouping the measured outputs of the system
$w \in R^l$ et $z \in R^l$:	Respectively include inputs and auxiliary outputs. n, m, l and p are positive integers

The matrices (A, B_1, B_2, C_1, C_2, D_{11}, D_{12}, D_{21} and D_{22}) are appropriately sized matrices.

BG Modeling Elements by LFT Representation

Modeling linear systems with uncertain parameters was developed in C. Sie Kam, we invite the reader to view the references for details on the modeling of uncertain BG components (R, I, C, FT and GY) Fig. 3.

We therefore limit this part to show the two methods of modeling uncertain BG elements and the advantages of BG-LFT for robust diagnosis.

Full BG-LFT can then be represented by the diagram in Fig. 3.

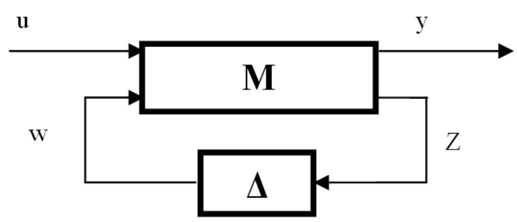

Fig. 2. Representation LFT for physical system

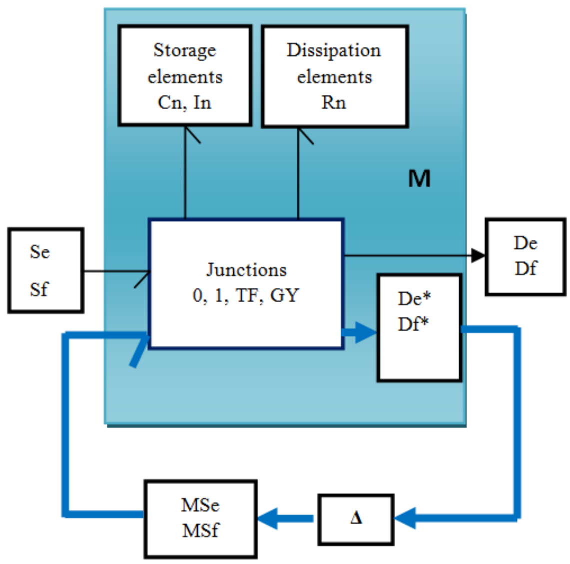

Fig. 3. Representation of BG-LFT

Generate Robust Residues

The generation of robust analytical redundancy relations from a clean bond graph model, observable and over determined be summarized by the following steps:

1st step: Checking the status of the coupling on the bond graph model deterministic preferential derived causality; if the system is over determined, then continue the following steps
2nd step: The bond graph model is made into LFT
3rd step: The symbolic expression of the RRA is derived from equations junctions. This first form will be expressed by:

- For a junction 0:

$$\sum b_i \, \mathrm{f}_{\mathrm{inc}} + \sum Sf + \sum w_i \quad (2)$$

- For a junction 1:

$$\sum b_i \, \mathrm{e}_{\mathrm{inc}} + \sum Se + \sum w_i \quad (3)$$

With the sum ΣSf of sources flows due to the junction 0, the sum ΣSe of the sources of stress related to junction 1, b = ±1 at the half-arrow into or out of the junction and e_{in} and f_{in} purpose are unknown variables, the sum Σw_i of modulated inputs corresponding to the uncertainties on the junction-related items:

4th Step: The unknowns are eliminated by browsing the causal paths between the sensors or sources and unknown variables
5th step: After eliminating the unknown variables, are uncertain as $\mathrm{RRA_S}$:

$$RRA : \Phi \begin{pmatrix} \sum \mathrm{Se}, \sum \mathrm{Sf}, De, Df, \tilde{D}e, \tilde{D}f, \\ \sum w_i, R_n, I_n, C_n, TF_n, GY_n \end{pmatrix} \quad (5)$$

- TF_n and GY_n are the nominal values of the elements and modules, respectively *TF* and *GY*
- R_n, C_n and I_n are the nominal values of the elements R, C and I

Analysis of Residuals Sensitivity

Analysis of residuals sensitivity has been developed in recent years. Indeed, the methods are proposed to evaluate these residuals. When residuals are assumed normally distributed around a known average statistical methods to generate normal operating thresholds are well suited (Basseville *et al*., 1987). In the event that the uncertainty does not operate at the same frequency as defects, filtering methods are suitable property (Han *et al*., 2002). While the actuators and sensors faults are determined using parity space (Henry *et al*., 2001; Henry and Zolghari, 2006). Unfortunately, these residues generation methods are not effective since they neglect the inter-parametric correlation (the thresholds are often overvalued and may differ).

The Bond Graph tool provides an effective solution to the problem of parametric dependencies since the generation BG-LFT automatically separates tailings and adaptive thresholds.

Generation of Indices Performance

To improve diagnostic performance, determine the indices performance (sensitivity index and defect detectability index).

Index Sensitivity (IS)

The index of parametric standardized sensitivity explained the evaluation of the energy provided by the residue uncertainty on each parameter by comparing it with the total energy provided by all uncertainties:

$$IS_{ai} = \frac{|a_i|}{d} \frac{\partial d}{\partial |a_i|} = \frac{|w_i|}{d} \quad (4)$$

- a_i: Uncertainty on the parameters
- $i \in \{R, C, I, TF, GY\}$
- w_i: Modulated entry for Uncertainty in the th *parameter*

Index Defect Detectability (ID)

The index defect detectability index represents the difference between the efforts (or streams) provided by defects in absolute terms and that granted by all the uncertainties in absolute value:

Junction 1:

$$ID = |Y_i||e_{in}| + |Y_s| - d \quad (6)$$

Junction 0:

$$ID = |Y_i||f_{in}| + |Y_s| - d \quad (7)$$

While defects detectability conditions will be:

- Undetectable fault: $ID \leq 0$
- Undetectable fault: $ID \rangle 0$

Robust Diagnosis of DC Motor by Bond Graph Approach

Bond Graph Model of DC Motor

Consider the circuit diagram of a DC motor and its bond graph model given in Fig. 4. On this system, we will detect and locate defects in the flow sensors (current by sensor Df_1 and speed by sensor Df_2).

Figure 5 shows the waveform of the current absorbed by the motor (a) and rotational speed of the motor (b).

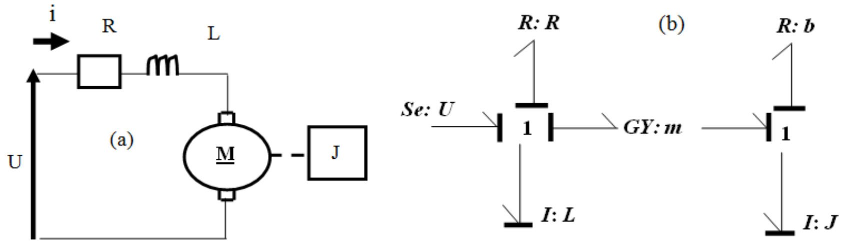

Fig. 4. (a) DC motor, (b) Bond Graph model of DC motor

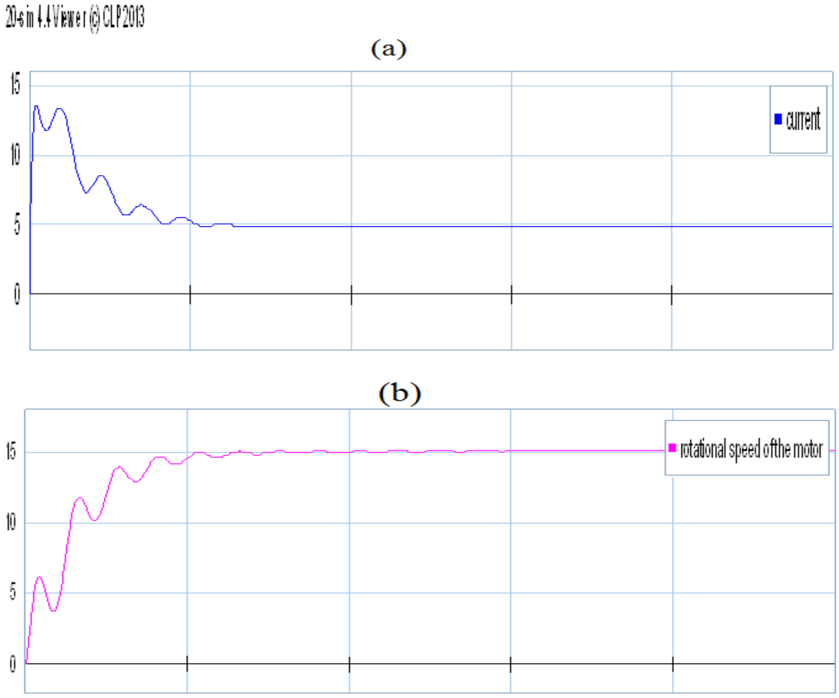

Fig. 5. (a) Current of the DC motor, (b) Speed of the DC motor DC motor

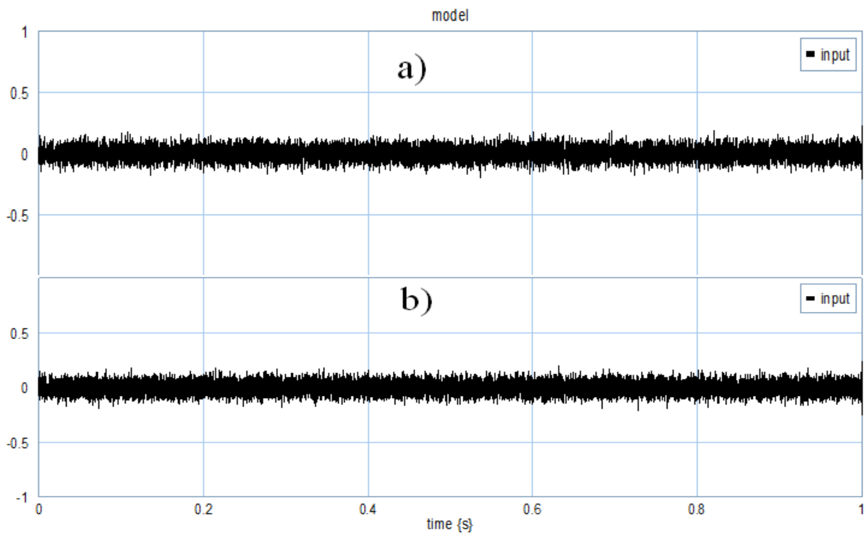

Fig. 6. Residual $r_1(t)$ in the normal operation, Residual $r_2(t)$ in the normal operation

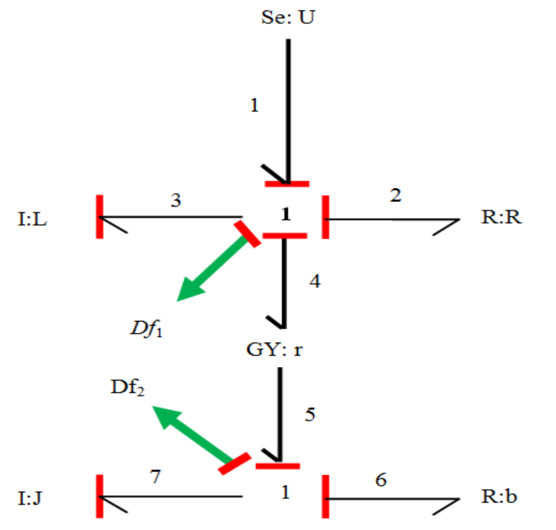

Fig. 7. BG Model of DC motor and sensors

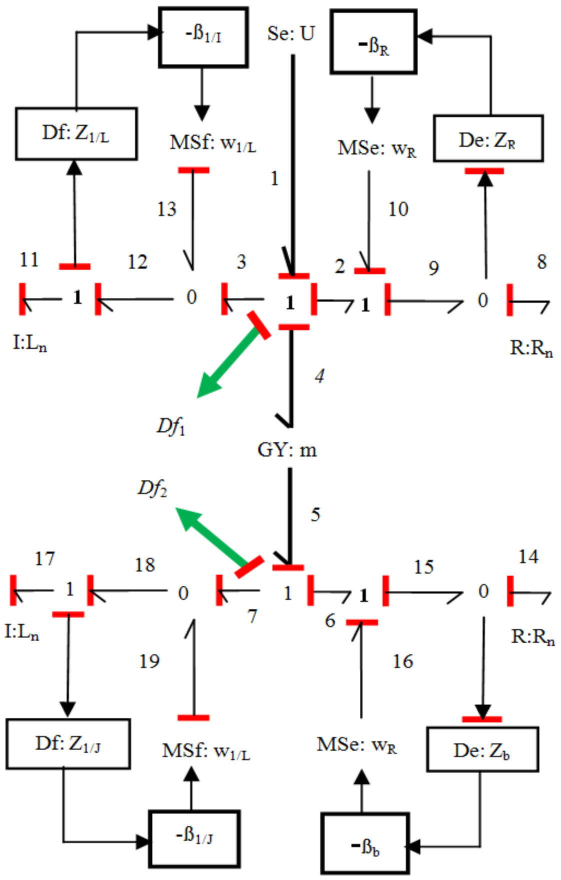

Fig. 8. BG-LFT Model integral causality of DC motor and sensors

Figure 6 shows the shape of the residues r_1 and r_2 in the case of normal operation. We note that residues paces converge to zero.

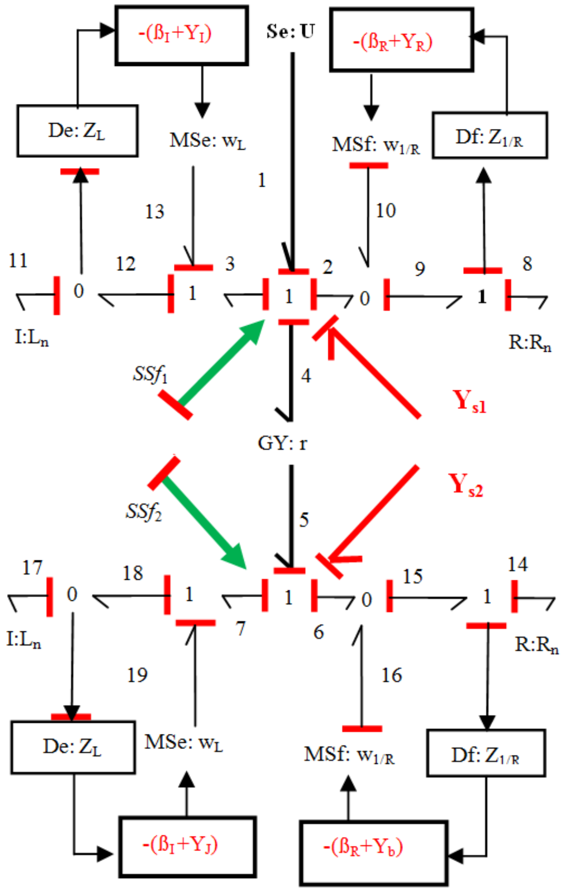

Fig.9. BG-LFT Model derived causality of DC motor and sensors dualization

The Fig. 7 shows the modeling of the DC motor by the bond graph approach with two detectors, the current sensor (Df_1) and the speed sensor (Df_2).

The Fig. 8 below shows the bond graph model in integral causality of the system using the LFT form.

To determine the residues, we must put the system in the formre derivative and also put sensors under dualized form (Fig. 9).

We have introduced two four parametric defects (Y_L, Y_R, Y_J and Y_b) and structural defects (Y_{s1} and Y_{s2})

Simulation of the DC Motor

The simulation of the current and the speed of the DC motor by the software 20-sim intended for industrial systems modeled by the bond graph approach in Fig. 4.

The Equations BG Model before Default

Junction 1_1:

$$e_2: SSf_1 \rightarrow \Psi_{Rn}(f8, e_8) \rightarrow e_2 = R_n .SSf_1$$
$$e_3: SSf_1 \rightarrow \Psi_{Ln}(f_{11}, e_{11}) \rightarrow e_3 = L_n .SSf_1$$
$$e_4: SSf_2 \rightarrow \Psi_{GY}(f_5, e_4) \rightarrow e_4 = m .SSf_2$$

The ARR1 equation before default can be written:

$$\begin{cases} ARR_1 = r_{1n} + d_1 \\ RRA : U\, R_n\, SSf_1\, L_n \dfrac{dSSf_1}{dt} - \text{m .SSf}_2 + w_R + w_L = 0 \\ r_n = U\, R_n\, SSf_1\, L_n \dfrac{dSSf_1}{dt} \\ d_1 = |w_R| + |w_L| \\ d_1 = |\delta_R\, R_n\, SSf_1| + \left|\delta_L\, L_n\, L_n \dfrac{dSSf_1}{dt}\right| \end{cases}$$

Junction 1_2:

e₅: $SSf_1 \rightarrow \Psi_{GY}(f_4, e_5) \rightarrow e_5 = m\,.SSf_1$
e₆: $SSf_2 \rightarrow \Psi_{Rn}(f_{14}, e_{14}) \rightarrow e_{14} = b_n\,.SSf_2$
e₃: $SSf_1 \rightarrow \Psi_{Ln}(f_{17}, e_{17}) \rightarrow e_{17} = J_n\,.SSf_2$

The ARR_2 equation before default can be written:

$$\begin{cases} ARR_2 = r_{2n} + d_2 \\ ARR_2 = \text{m .SSf}_2\, b_n\, SSf_2\, J_n \dfrac{dSSf_2}{dt} \\ + w_b + w_J = 0 \\ r_{2n} = m\, \text{.SSf}_2\, b_n\, SSf_2\, J_n \dfrac{dSSf_2}{dt} \\ d_2 = |w_{1/b}| + |w_J| \end{cases}$$

The ARR_1 equation after default can be written:

$$\begin{cases} ARR_1 = r_{1n} + d_1 \\ ARR_1 = Y_{s1} + U\, R_n\, SSf\, L_n \dfrac{dSSf_1}{dt} \text{m .SSf}_2 \\ + w_{1/R} + w_L = 0 \\ r_{1n} = Y_{s1} + U\, R_n\, SSf_1\, L_n \dfrac{dSSf_1}{dt} \\ d_1 = |w_{1/R}| + |w_L| \\ d_1 = |\delta_R\, R_n\, SSf_1| + \left|\delta_L\, L_n\, L_n \dfrac{dSSf_1}{dt}\right| \\ + |Y_R e_{Rn}| + |Y_L e_{Ln}| \end{cases}$$

The ARR_2 equation after default can be written:

$$\begin{cases} ARR_2 = r_{2n} + d_2 \\ ARR_2 = Y_{s2} + \text{m .SSf}_2\, b_n\, SSf_2\, J_n \dfrac{dSSf_2}{dt} \\ + w_b + w_J = 0 \\ r_{2n} = Y_{s2} + \text{m .SSf}_2\, b_n\, SSf_2\, J_n \dfrac{dSSf_2}{dt} \\ d_2 = |w_{1/b}| + |w_J| \\ d_2 = |\delta_R\, b_n\, SSf_1| + \left|\delta_L\, j_n\, j_n \dfrac{dSSf_1}{dt}\right| \\ + |Y_b e_{bn}| + |Y_J e_{Jn}| \end{cases}$$

Conclusion

The choice of the LFT form for modeling with parametric uncertainties the bond graphs allowed to use a single tool for the systematic generation of indicators formal uncertain defects. These parametric uncertainties are explicitly introduced on the physical model with its graphics architecture, which displays clearly on the model of their origins.

Uncertain ARR generated are well structured, showing separately the contribution Energy uncertainties fault indicators and facilitating their evaluations in the step of decision by the calculation of adaptive thresholds for normal operation. The diagnosis performance is monitored by an analysis of the residues of sensitivity to uncertainties and defects. The defect detectability index is defined to estimate a priori detectable value of a default and to measure the impact of default on an industrial process. The parametric sensitivity index is used to determine parameters that have the most influence on the residues. From a practical standpoint, the fields of application of this method are very broad due to the energy aspect and multi physics of bond graphs and the LFT form used to model the influence of uncertainties about the system. The developed procedure is implemented on a software tool (controllab products 20-sim version 4.0) to automate the generation of LFT models and uncertain ARR.

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Author's Contributions

Abderrahmene Sallami: Author made considerable contributions and design, analysis and data interpretation.

Nadia Zanzouri: Author contributes to the review of article critical of his important intellectual content.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of other authors have read and approved the manuscript and no ethical issues involved.

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