

Fault Diagnosis in DC Motor Using Bond Graph Approach

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Abstract. The Bond Graph (BG) shows a direct correspondence between their component parameters and physical phenomena to be modeled, not only a system model is obtained, but also component parameter failure representations, since the BG model obtained is useful like a diagnosis model too.

Using like case of study a direct current (dc) motor to implement the application, this paper shows how to obtain a fault tree to define the first set of fault hypothesis, and then, for using a temporal graph to define the fault, i.e. in order to reduce the set of fault hypothesis to only one element.

Key words. Fault diagnosis, causality, dc motor, Bond Graph, quantitative and qualitative model-based approaches.

1. Introduction

Fault diagnosis has been presented in many industrial processes as an indispensable part of the control systems to be able to guarantee the reliability and availability of the process (Iserman et al. 1996; van Schrick Dirk 2000; Vergé 1994).

It is a stage of the supervisory system, which has the objective of indicating undesired or forbidden process states and to take appropriate actions in order to maintain the operation and to avoid damages or accidents. The supervisory system blocks are shown in figure 1.

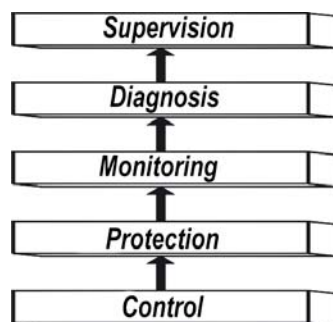


Figure 1. Supervisory system

The diagnosis part in fault diagnosis systems shows a hole between qualitative and quantitative analysis (van Schrick Dirk 2000; Vergé 1994), it is necessary to apply, in many cases, statistical, operator experience, heuristic and functional information to complete the diagnosis stage. In this paper a method

was developed that integrates studies where the BG has been used for fault diagnosis, but here is presented a new manner to interpret the energy flux immediately after a fault is presented. The paper is organized as follows. In section 2 the BG basics are given and then in section 3, the dc motor circuit and BG model of it are presented. Section 4 shows the proposed method using BG elements and its order to be applied to the systems and the proposed method is applied to dc motor; a fault in parameter R_a is used as example. Then, in section 5, the proposed method is applied to dc converter-motor set system. The conclusions are given in section 6.

2. Bond Graph Basics

Bond Graph (BG) approach has been used in many senses: simulation, modeling and control, show itself like a very useful tool for application in several systems. This is a good tool to representation models based on physical concepts using a finite symbols for application to any systems; provides structured approach to system dynamics modeling without loss of the physical sense, that takes advantage to diagnosis. In table 1 are shown the equivalences between elements from several domains (Blundell 1982; Broenink 2001; Gawthrop et al. 1996; Karnopp 1990).

Table 1. Equivalences between domains

Domain	Electrical	Mechanical rotational	Hydraulic	Thermal
Bond	Electrical	Shaft, axis, arm	pipes, pipelines	Ducts, pipelines, bodies
Effort	Voltage (v.e)	Torque (τ)	Pressure (P)	Temperature (T)
Flow	Current (i)	Angular velocity (ω)	Flux velocity (Q_v)	Entropy (E)
Effort store	Flux linkage (λ)	Angular momentum (m)	Pressure moment (L)	No equivalent
Flow store	Electric charge (Q)	Angular position (θ)	Flux accumulator (V)	Total heat (Et)
Resistance	Electrical resistance (R)	Friction (f)	Fluidic dissipator	Thermal dissipator
Inertance	Inductor (L)	Rotational inertia (J)	Fluidic inertia, mass (I)	No equivalent
Capacitance	Capacitor (C)	Compliance (k)	Hydrostatic accumulator (C_v)	Thermal capacitance (Ct)
Effort source	Voltage source	Pump, torque, motor	Pressure pump	Diesel engine
Effort flow	Current source	Shaft driver	Hydrostatic pump	Thermal movement
Transformer	Electrical transformer	Gear arrangement (1:2)	Pipe reducer	Turbine head
Gyration	DC motor	Gears	No equivalent	No equivalent
0 junction	Parallel circuit	Shaft gear	Parallel circuit	Parallel circuit
1 junction	Series circuit	Weights junction	Series circuit	Series circuit

In BG common variables *effort* and *flow* are used in each domain and their product is power, as energy derivative, is a common concept relating these systems. From the viewpoint of energy flow, using BG, system components and physical phenomena are classified into five basic types: 1) energy conserving or storing elements (I and C), 2) energy dissipating elements (R), 3) energy source elements (S_e and S_f), 4) energy

conversion elements (*TF* y *GY*), and 5) junction elements (Blundell 1982; Broenink 2001; Gawthrop et al. 1996; Karnopp 1990). Each element with characteristic relationship are shown in table 2. We can think in junction as common effort (0) or common flow (1).

Table 2. Bond Graph elements

Symbol	Element type	Element name	Symbol (preferred causality)	Causal Relation (preferred causality)
Se	Source	Effort source (fix causality)	$S_e \rightarrow$	$e(t) = \dot{E}(t)$ is a effort function
Sf		Flow source (fix causality)	$S_f \leftarrow$	$f(t) = F(t)$ is a flow function
C	Store	Capacitance	$C \leftarrow$	$e = \Phi_C^{-1} \left(\int f dt \right)$ Φ_C is a parametric capacitance function
I		Inertance	$I \rightarrow$	$f = \Phi_I^{-1} \left(\int e dt \right)$ Φ_I is a parametric inertance function
R	Disipator	Resistance	$R \leftarrow$ $R \rightarrow$	$e = \Phi_R(f)$ $f = \Phi_R^{-1}(e)$ Φ_R is a parametric resistance function
TF	Transductor	Transformer	$\frac{\phi_1}{f_1} \rightarrow \frac{\phi_2}{f_2}$	$f_2 = n f_1$ $e_1 = n e_2$
GY		Gyrator	$\frac{\phi_1}{f_1} \rightarrow \frac{e_2}{f_2}$	$e_2 = r f_1$ $e_1 = r f_2$
0	Junction	0 junction		$e_1 = e_2 = \dots = e_i$ $\sum_{j=1} f_j = 0$
1		1 junction		$f_1 = f_2 = \dots = f_j$ $\sum_{i=1} e_i = 0$

It is necessary give to each element a causality, that means what direction the effort takes, and therefore, the flow direction, due to in each bond the conjugate flow-effort are in opposite directions. To assign the causality, a causal stroke indicates the effort direction, what tell us which variable is outside of the element (Blundell 1982; Broenink 2001; Gawthrop et al. 1996; Karnopp et al. 1990).

Exist rules to assign causality and generate the equations describing the system. It is preferred an integral causality, that it is determined for storing elements *I* and *C*, by the relationships:

$$q = \frac{1}{C} \int_0^t f(\tau) d\tau \quad (1) \quad p = \frac{1}{I} \int_0^t e(\tau) d\tau \quad (2)$$

called *integral causality*, and makes the equations obtaining an easy way.

From (1) and (2) we can obtain the generalized states combining the equations obtained from the other elements, this variables are the *state variables* from the BG model. Using the table 3 we can to obtain the more common variables, for that, it should be has in mind that an effort integral is a *momentum generalized* and a

flow integral is a *displacement generalized* (Blundell 1982; Broenink 2001; Gawthrop et al. 1996; Karnopp 1990).

Table 3. Generalized states

Domain	Gen.mom. ($\int e$)	Gen.disp. ($\int f$)
Mechanical Translational	momentum p	displacement x
Mechanical Rotational	ang.momentum m	ang. displacement θ
Electromagnetic	flux linkage ϕ	charge q
Hydraulic	pressure mom P_p	volume V
Thermic	NONEXISTENT	entropy E

3. DC motor model

A dc motor in independent excitement or permanents magnets configuration is presented in figure 2. Here, the armature voltage, V_a , is constant as well as the field current, i_f .

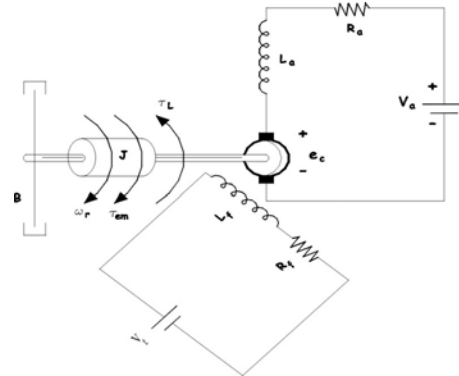


Figure 2. DC motor circuit

The mathematical model of the system can be described in dynamical form starting from the bond graph model presented in figure 3. To obtain the equations the generalized variables are used: p_3 related to electrical part and p_8 related to mechanical part.

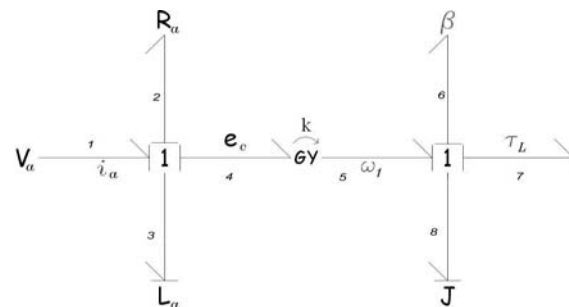


Figure 3. BG of dc motor

From figure 3 the equations that describes the causal interactions are:

$$e_3 = e_1 - e_2 - e_4 \dots (3) \quad f_3 = \frac{p_3}{L_a} \dots (8)$$

$$f_1 = f_2 = f_3 = f_4 \dots (4) \quad f_8 = \frac{p_8}{J} \dots (9)$$

$$e_8 = e_5 - e_6 - e_7 \dots (5) \quad e_6 = \beta f_6 \dots (10)$$

$$f_5 = f_6 = f_7 = f_8 \dots (6) \quad e_4 = k f_5 \dots (11)$$

$$e_2 = R_a f_2 \dots (7) \quad e_5 = k f_4 \dots (12)$$

Here, the state variables are electric momentum (magnetic flux linkage) and mechanical momentum (angular momentum). The state equations from above describing the system are:

$$\begin{bmatrix} \dot{p}_3 \\ \dot{p}_8 \end{bmatrix} = \begin{bmatrix} -\frac{R_a}{L_a} & -\frac{k}{J} \\ \frac{k}{L_a} & -\frac{\beta}{J} \end{bmatrix} \begin{bmatrix} p_3 \\ p_8 \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} V_a \\ \tau_L \end{bmatrix} \quad (13)$$

but we are interested in *current* and *velocity* as the *output variables*, which are the measured variables from a dc motor, then:

$$\begin{bmatrix} i_a \\ \omega_r \end{bmatrix} = \begin{bmatrix} 1/L_a & 0 \\ 0 & 1/J \end{bmatrix} \begin{bmatrix} p_3 \\ p_8 \end{bmatrix} \quad (14)$$

Now, we use a parallel model (Leitch 1993) to generate the residual that shows the system changes in the fault case. Observing these residuals is possible to apply the diagnosis method noting changes in each variable measured. We can establish a threshold to decide when the residual is not null. This threshold depends on the value due to the 2% of steady state of the signal measured, i.e. current and velocity in this case. If the value is 2% upper (or lower), then the residual is non-zero.

4. Fault diagnosis method

The fault diagnosis method proposed here, is based using researches that has been used BG to derive some results focused in diagnosis. The stages of this method are shown in figure 4.

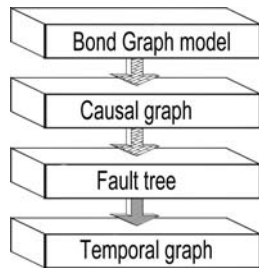


Figure 4. Fault diagnosis method

The *causal graph* is a consequence of the causal relationships between elements, obtained in direct form from the BG of the system (Isermann 1996; Karnopp et al. 1990; Mosterman et al. 1997; Mosterman et al. 1995).

This graph is seemed to the sign flow graph used in classic control. To construct the causal graph reference nodes are necessary, these are selected from the junction 1 (or 0) and using the equation that describes it. For the figure 3 model we use the equations (3) and (5), and we relate each component until fits the other equations. Each node constitutes

blocks that are the bases of the causal graph. Arrows connect variables and parameters, and the relation between variables is indicated over the link (Mosterman et al. 1997; Mosterman et al. 1995).

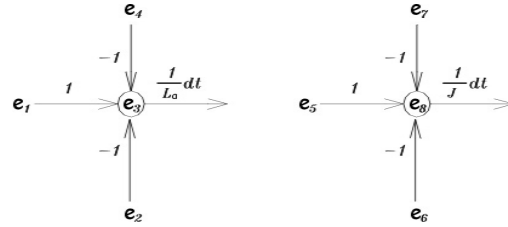


Figure 5. Nodes (blocks) to form causal graph

The causal graph is done joining the reference nodes. Causal graph for dc motor is shown in figure 6.

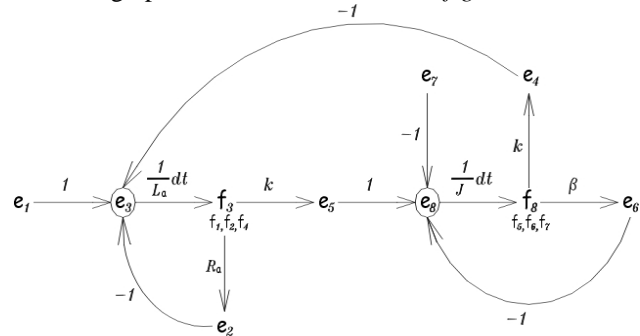


Figure 6. Causal graph of dc motor

From this causal graph we obtain the next elements of the fault diagnosis method proposed. It follows the fault tree, which shows the qualitative variations when an observed variable has changed.

A qualitative variation refers to change from nominal value. In this work, the three symbolic terms low [-], normal [0] and high [+] are used. Qualitative transitions occur at the boundary endpoints.

Mathematically, the qualitative value of x , denoted $[x]$, defined as the deviation from a reference point x_0 is given as $[x] = \text{sgn}(x - x_0)$. When the reference is a range, the qualitative value of x is defined as

$$\begin{aligned} [x] &= '-' \text{ when } x < x_0^- \\ [x] &= '0' \text{ when } x_0^- \leq x \leq x_0^+ \\ [x] &= '+' \text{ when } x_0^+ < x \end{aligned}$$

where x_0^- and x_0^+ are the lower and upper range endpoints, respectively.

The fault tree derived from BG is obtained for each variable of interest and can be built using back propagation in the causal graph (or antecedents and consequents table), in the next form (Karnopp et al. 1990; Vergé et al. 1994):

- Start from the variable of interest with its qualitative value and track back the sign through the path assigning the right qualitative value (from the variable of interest, propagate the qualitative

value, take this variable as the consequent and write the antecedent as the next consequent).

- Join the sign by means of arrow (a branch) and continue the track back for all the signs across the variables (join the consequents to antecedents by means of arrows or branches).
- Propagation is terminated along a path when a conflicting assignment is reached.

The fault tree can be gotten from relationships (3)-(12), more precisely from causal relationships given for the BG rules (Blundell 1982; Broenink 2001; Karnopp et al. 1990; Mosterman et al. 1997). In *table 4* this relationships are presented, named antecedents and consequents table.

Table 4. Antecedents and consequents

Component	Antecedent	Consequent
	$1/C \circ f$	e
	$1/I \circ e$	f
	$1/R \circ e$	f
	$R \circ f$	e
	f_1, e_2, n	f_2, e_1
	$f_2, e_1, 1/n$	f_1, e_2
	f_1, f_2, r	e_1, e_2
	e_i $f_1, f_2, -f_3, \dots$	e_1, e_2, e_3, \dots f_j
	f_j $e_1, -e_2, -e_3, \dots$	f_1, f_2, f_3, \dots e_i
	Se	e
	Sf	f

Using qualitative values (-, 0, +), starting from the variable observed with its value obtained from residual, one propagates this value through the branches. With help of *table 4* is built the *table 5* for dc motor.

The fault tree for the variables of interest, e_3 , related to the current i_a , and e_8 , related to the velocity ω , with qualitative value [-], are shown in *figure 7*. In these trees, the qualitative value is propagated using logical operations with positive values.

Table 5. Antecedents and consequents for dc motor causal graph

Antecedents		Consequents
$\frac{1}{L_a}$	e_3	f_3
	f_3	f_1, f_2, f_4
	$e_1, -e_2, -e_4$	e_3
$\frac{1}{J}$	e_8	f_8
	$e_5, -e_6, -e_7$	e_8
	f_8	f_5, f_6, f_7
K	f_4, f_5	e_4, e_5
R_a	f_2	e_2
β	f_6	e_6

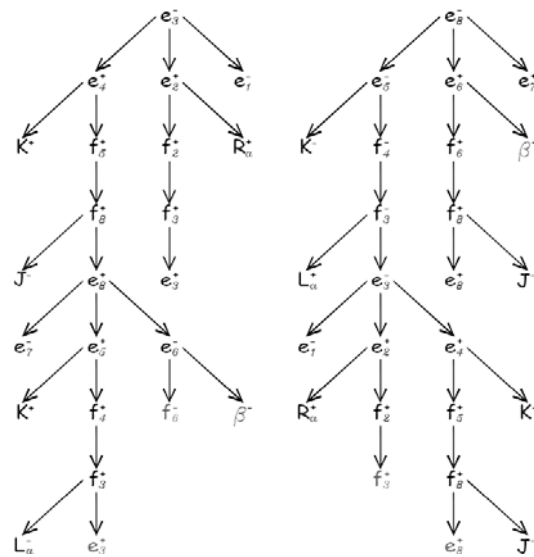


Figure 7. Fault trees for e_3^- and e_8^-

A suggested algorithm to generate the first fault hypothesis set could be the following:

1. Construct an antecedents and consequents table, or from causal graph use back propagation.
2. Construct the fault tree for the variables of interest.
3. Observe what type of qualitative variation presents the observed variables through the residuals, and which they are matched with the qualitative changes in the fault tree.
4. Form the hypothesis fault set with the parameters that match the same qualitative comportment in fault trees.

So far, the blocks shown in *figure 4* has been developed by others researchers, but the final block about using the temporal graph is suggested by Mosterman in ((Mosterman et al. 1997; Mosterman et al. 1995)).

One can to predict how will be the comportment of the signal and its derivatives before the system reach the new steady state after the fault has occur by means

of the *temporal graph* ((Mosterman et al. 1997; Mosterman et al. 1995). This graph provides the signatures that indicate the comportment before the new steady state is reached. The following steps to obtain the causal graph are used:

1. Start from one of the parameters that are included in fault hypothesis set and propagate its qualitative value through the graph.
2. When the signal cross through a link with a differential, then mark this with \uparrow or \downarrow if qualitative value increase or decrease. This indicates the first derivatives and the qualitative signature.
3. The propagation continues until reach a second derivative and all the observed variables have been covered by the second derivative.
4. Signatures associates to derivatives with small time constants are rejected, if there were two variables with different signatures.

Temporal graph for R_a^+ is shown in figure 7.

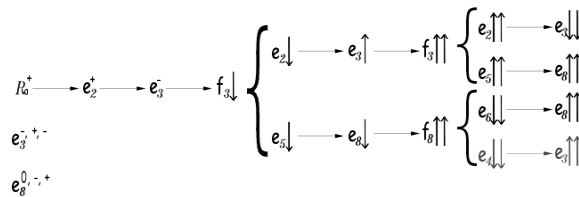


Figure 7. Temporal graph for R_a

As example, it is presented the residual (figure 8) from R_a fault in the electric part of dc motor.

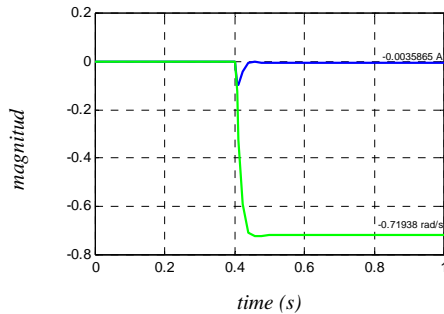


Figure 8. Residuals when R_a is faulty

It is observed that, current and velocity decrease, then we only construct fault trees for e_3 and e_8 with qualitative values (-).

These fault trees are shown in figure 7, and can be observed parameters K , R_a , J have the same qualitative signature in both fault tree, then the first hypothesis fault set is formed by $\{R_a^+, J^-, K^{+-}\}$. The others parameters are rejected because have different qualitative value in each tree.

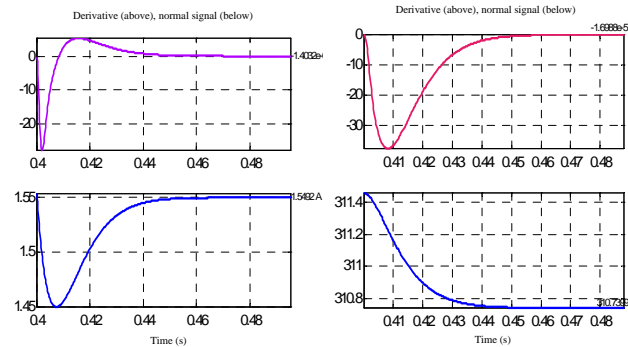
When use the temporal graph, it is obtained the signatures presented in table 6. From figure 9, the normal signal and first order derivative that match signatures against shown in table 6 are R_a^+ , J^- , but J is

discarded because is differential related, i.e. the fault comportment continue while time go on.

Table 6. Signatures for parameters in hypothesis fault

R_a^+	e_3^{+-}	$e_8^{0,+-}$
J^-	e_3^{+-}	e_8^{+-}
K^+	$e_3^{0,+-}$	e_8^{+-} , discarded

As it is necessary obtain derivatives, can be used state variable filters, if the system is linear, like treated here, or use numerical methods to generate the derivatives. In figure 9 are shown the normal signal and its derivatives for current and velocity.

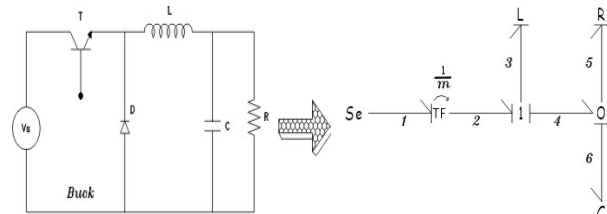


(a) Current i_a (b) Velocity ω_r

Figure 9. Derivatives and normal signal of measured variables

5. DC converter-motor system set

To model in BG a dc converter it is introduced an element that describes the discontinuous behavior elements like the switching devices included in the converter. First, is modeled a reductor converter (buck) introducing the discontinuous element as a *TF* bond graph element with a transformer modulus m , which takes 1 and 0 values depending the conmutations states of the switching device, namely, duty cycle. The



converter circuit is shown in the left side of figure 10.

Figure 10. DC converter circuit and BG model

The BG model is shown in the right side of figure 10. When the full bridge dc converter work in one quadrant, as shown in figure 11, the model can be interpreted like the shown in figure 10, so the BG model is the same shown in the right side of figure 10.

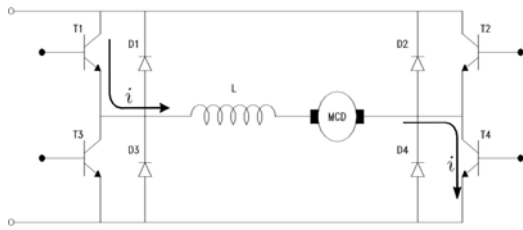


Figure 11. Full bridge dc converter circuit

Looking the figure 6, e_1 corresponds to dc converter output, and it is possible to add the causal graph of dc converter alone, shown in figure 12 a) to obtain the causal graph of all the system, as is presented in figure 12 b).

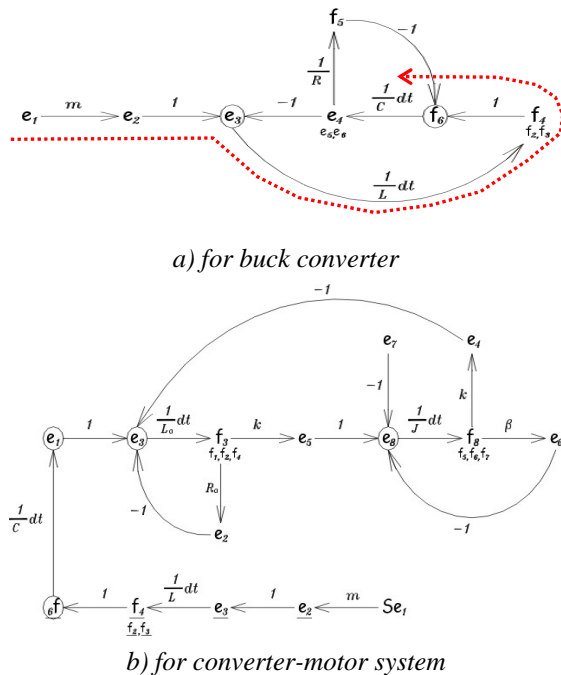


Figure 12. Causal graph of dc converter

The next table 7, summarize the simulated faults applying the proposed method.

Table 7. Summary of faults

Fault	Diagnosis (minimum hypothesis set)	Residual comportment
J^+	$\{J^+\}$	Transitory
J^-	$\{J^-\}$	Transitory
K^+	$\{R_a^+, K^+, m^+\}$	Permanent
K^-	$\{R_a^-, K^-, m^-\}$	Permanent
R_a^+	$\{R_a^+, m^+\}$	Permanent
R_a^-	$\{R_a^-, m^-\}$	Permanent
L_a^+	$\{L_a^+\}$	Transitory
L_a^-	$\{L_a^-\}$	Transitory
β^+	$\{\beta^+\}$	Permanent
β^-	$\{\beta^-\}$	Permanent
m^+	$\{R_a^+, K^+, m^+\}$	Permanent
m^-	$\{m^-\}$	Permanent

6. Conclusion

The fault diagnosis method presented in this paper use the BG approach. The final stage of fault diagnosis needs to analyze the comportment over the time, and match this comportment against the provided by the temporal graph to decide where is the fault exactly by means of reduction of the fault hypothesis set. Although the method cannot reduce the fault hypothesis set to only one element in some cases, shows it as a new attempt to unify the qualitative and quantitative reasoning in fault detection and can apply the integration of fault detection methods because the equations allow it.

The method is easy to apply and sequential to perform, does not require another tool more than only BG elements. However, the limits of this method are reached when the system is non linear. Some interesting questions remain open in the frame-work of this case, for example the selection between:

- Analytical redundancy relations (ARR) with parity equations for non-linear systems (Staroswiecki et. al 1991).
- Multiple models approach (Chen at al. 1999, Boskovic et al. 2003).

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