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# Sensor Placement for Diagnosability Analysis in Thermofluid Processes

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*Abstract*— **A system in process engineering's safety is based on a monitoring system characterized by its ability to detect and to isolate faults. Considering single faults diagnosis, the existent monitoring systems treat only one category of additive faults at a time (actuator faults or sensor faults). The present paper considers thermofluid processes; the main objective is to identify the category of components (hydraulic actuators, thermal actuators, hydraulic sensors and thermal sensors) to which belongs the faulty element. Then one can seek the fault in the right category thanks to the existing methods. The innovative interest is thus to be able to isolate two component faults of different categories. On a second time, the set of thermal sensors is considered and an important result on their diagnosability is deduced. An application to an interconnected network of components in a thermofluid installation illustrates our results.**

*Index Terms*— **Thermodynamic Bond graphs, Fault Detection and Isolation (FDI), Diagnosis, Signature faults, Analytical Redundancy Relations (ARRs).**

## I. Introduction

A safe and reliable plant depends on Fault Detection and Isolation (FDI) procedures. The FDI problem has received considerable attention in the past ten years [1], [9]. We are interested in the comparison between the actual system behavior (provided by the sensors) with the reference behaviors describing the normal operation (for fault detection) or different kinds of faulty ones (for fault isolation/ estimation).

There has been a significant research in the area of model based fault detection. The analytical redundancy approach consists in finding the over constrained subsystem (representing the monitorable part of the overall system) since it is the only one to exhibit some redundancies. The first step consists in generating a set of residuals (relations between the known variables of the system [2], [4]. These relations, called Analytical Redundancy Relations (ARRs), are special signals that reflect the discrepancy between the actual and the reference behaviors. The ARRs can be directly generated in a formal format using a bond graph tool [14].

The linearized bond graph model, thanks to its structural and causal properties, allows the diagnosability (ability to detect and to isolate the faults) of actuators to be deduced without need of calculation [5], [12]. While the BG tools are no longer valid for non-linear systems, flatness topology is introduced to help in the design of a monitoring architecture for actuators [7]. In fact, sensor placement on flat outputs provides better insight into the effect of actuator faults and consequently their diagnosability can easily be analyzed. In spite of the importance of sensors as main elements in the control design, they have not received much attention in the literature and usually physical redundancy is used to deal with such faults.

Alternatively, some authors have proposed solutions to the FDI problem for a non-linear system class in an algebraic and differential setting; see [5], [10]. Based on the algebraic observability of the variable which models the failure presence, the diagnosis problem in non-linear systems is tackled [3].

Despite many extensive studies in this area, the existent monitoring systems consider at a time only one type of components (actuators, sensors or physical component). However, rather few results concern the monitoring of any type of components in process engineering. The major contribution of this paper is therefore to propose a diagnostic architecture for these set of components so that the diagnosability of any components can be deduced using the preceding results. This diagnostic architecture exhibits the category of components to which belongs the faulty element thanks to the existing sensors and the location of possible additional sensors. Indeed, many structural properties can be deduced investigating the special form of the state equations for this kind of processes.

On a second time, the set of sensors is considered and an important result on the diagnosability of thermal sensors is deduced. In fact, it will be shown that all thermal sensors are monitorable which drastically reduce the size of the problem.

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The rest of this paper is organized as follows: while the monitored process is a complex non-linear model combining thermal and hydraulic energies, section 2 begins by describing the developed monitoring architecture, thermal sensors are then considered and an important result concerning their diagnosability is obtained. An application to a network of interconnected components in thermofluid processes illustrates our results. Finally, the paper is closed with some concluding remarks.

## II. Monitoring of non linear systems in process engineering

Consider a coupled multienergy thermofluid process. The state equation form describing the system depends on the modeled physical phenomenon (saturated, under saturated...). The starting point of the implementation of a monitoring algorithm is the Process and Instrumentation Diagram (PID) of the considered process. It represents the architectural process model noted $\Sigma$. Let $n$ be the number of thermofluid components in $\Sigma$: COMPS = {COMP1… COMP$n$}. These components can be elements, which transport energies (piping, piping with pump, piping with valve...), which store energies (tank, accumulator, boiler) or energy sources (pump, heater...). While pseudo BGs are in general used, the state variables are the displacement variables (integral of flow variables): the mass and the internal energy [11]. The inertia of the fluid due to the mass of the fluid flowing through the pipe can be considered. In this case, the state variable is the impulsion (usually neglected because of the low velocities of the real fluid).

In this section is considered the fault detection and isolation of thermofluid processes in a modular fashion as follows:

1) the set of hydraulic sensors,
2) the set of thermal sensors,
3) the set of hydraulic actuators and
4) the set of thermal actuators.

Let us consider the class of non-linear systems described by [16]:

$$\begin{aligned} \dot{x}(t) &= f(x,u) \\ y(t) &= g(x,u) \end{aligned} \tag{1}$$

where $x$, $u$ and $y$ are respectively a state vector, a known input vector and the output, $f$ and $g$ are assumed to be known analytical vector functions. Before starting the main results, a useful proposition is recalled:

**Proposition 1.** [16] *A sufficient condition for a nonlinear system described by the above equations to have analytical redundancy relations is the analyticity of f and g. In this case, the derivation of each output $y_i$ to an order $s_i$ yields to a system of $\sum_i (s_i+1)$ equations such that:*

$$\bar{y} = G(x,\bar{u}) \tag{2}$$

*$\bar{y}$ is the set of output variables and their derivatives and $\bar{u}$ the corresponding set of input variables and their derivatives.*

*There are then $\sum_i (s_i+1) - r_x$ analytical redundancy relations under the form:*

$$w(\bar{y},\bar{u}) = 0 \tag{3}$$

*with* $r_x = rank\left[\dfrac{\partial G(x,\bar{u})}{\partial x}\right]$.

Consider a class of nonlinear thermofluid systems of state and output equations (4). A study of their form is particularly significant for the diagnosability.

$$\begin{cases} \dot{x}_H = f(x_H, u_H) \\ \dot{x}_T = g(x_H, x_T, u_H, u_T) \\ y_H = h(x_H) \\ y_T = l(x_H, x_T) \end{cases} \tag{4}$$

$f$, $g$, $h$ and $l$ are known non-linear analytical functions, where $h$ is an invertible one. The indices $H$ and $T$ designate respectively the hydraulic and the thermal variables. This corresponds physically to a thermofluid process in the under saturated case (the pressure and enthalpy or temperature are independent), but the internal energy depends on the total stored mass. The state equations form in saturated case are complex, some of them are given in [11].

Consider four categories of components (hydraulic actuators, thermal actuators, hydraulic sensors and thermal sensors), the main objective of this section is to develop the isolability condition of the cited elements: which component is faulty?

Within this framework, several theorems and corollaries can be stated based on proposition 1. *Those results are important for an optimal sensor placement in industrial processes*. Suppose that all hydraulic actuators are detectable by hydraulic and thermal sensors. All thermal actuators are supposed to be detectable by thermal sensors.

**Theorem 1.** (*Under Saturated Case*) *By installing any hydraulic sensor, the set of hydraulic actuators becomes monitorable with the set of thermal actuators: the faults that affect those actuators are detectable and isolable* (*distinguishable*).

**Proof.** Apply proposition 1 to equation (4). In our case, each hydraulic output $y_{iH}$ (resp. thermal output $y_{jT}$) is derived to an order $s_{iH}$ (resp. $s_{jT}$).

A system of $(\sum_i (s_{iH}+1)+\sum_j (s_{jT}+1))$ equations is obtained (equation 5).

$$\begin{cases} \bar{y}_H = G_H(x_H, \bar{u}_H) \\ \bar{y}_T = G_T(x, \bar{u}_H, \bar{u}_T) = G_T(x_H, x_T, \bar{u}_H, \bar{u}_T) \end{cases} \quad (5)$$

The obtained $\sum_{i,j}(s_{iH}+s_{jT}+2)-r_{xH}-r_{xT}$ analytical redundancy relations are under the form:

$$RRA: w(\bar{y}_H, \bar{y}_T, \bar{u}_T, \bar{u}_H) = 0 \quad (6)$$

With

$$r_{xH} = rang\left[\frac{\partial G_H(x_H, \bar{u}_H)}{\partial x_H}\right],\ r_{xT} = rang\left[\frac{\partial G_T(x, \bar{u}_H, \bar{u}_T)}{\partial x}\right]$$

$s_{iH}$ is the order of derivation of the hydraulic output $h_i$ and $s_{jT}$ the order of derivation of the thermal output $l_j$.

Among these ARRs, some relations depend on hydraulic energy only. These ARRs are associated with hydraulic sensors. From hydraulic point of view, we distinguish the pressure or level sensors and the hydraulic flow sensors. The non-linear state equations in the monophasic case can be written as follows:

$$\begin{aligned} \dot{x}_H &= f(x_H, u_H) \\ y_H &= h(x_H) \end{aligned} \quad (7)$$

This sub hydraulic model is an independent model with respect to thermal effects where $f$ and $h$ are two analytical functions. The obtained $\sum_i (s_{iH}+1)-r_{xH}$ analytical redundancy relations are of the form:

$$RRA_H:\ w_H(\bar{y}_H, \bar{u}_H) = 0 \quad (8)$$

with $r_{xH} = rank\left[\frac{\partial G_H(x_H, \bar{u}_H)}{\partial x_H}\right]$ and $s_{iH}$ the order of the derivation of the output $h_i$.

The remaining $\sum_i (s_{iT}+1)-r_{xT}$ redundancy relations are the thermal ARRs associated to thermal sensors, which we note:

$$RRA_T:\ w_T(\bar{y}_T, \bar{u}_T, \bar{u}_H, \bar{y}_h) = 0 \quad (9)$$

Table 1 shows the corresponding signature faults matrix. $RRA_H$ and $RRA_T$ are the set of residuals deduced respectively from hydraulic and thermal model. A "*" signifies that we have at least a "1" in each column. ("1"), ("0") in the i^th row and j^th column means that the i^th ARR ($ARR_i$) is sensible (not sensible) to the j^th failure), this is verified since all the actuators are detectable.

TABLE I
SIGNATURE FAULT MATRIX

| ***RRAs*** | $\bar{u}_H$ | $\bar{u}_T$ | $\bar{y}_H$ | $\bar{y}_T$ |
|---|---|---|---|---|
| $\boldsymbol{RRA_H}$ | * | 0 | * | 0 |
| $\boldsymbol{RRA_T}$ | * | * | * | * |

From a graphical point of view, it is easy to deduce that there is path from hydraulic sources ($u_H$) to thermal and hydraulic sensor (thermal and hydraulic state). However, there is path from thermal actuator to only thermal state (sensor). Based on the structural and causal properties given in [15], it is easy to verify the Boolean failure signature vectors of the hydraulic control sources $u_H$ and the thermal control sources $u_T$ given in table 1.

While the Boolean failure signature vectors of the hydraulic control sources $u_H$ and the thermal control sources $u_T$ are different and non-null, the failures that may affect them can be detected and isolated.

**Corollary 1.** *In the under saturated case, the set of hydraulic sensors is monitorable with the set of thermal sensors.*

The proof is straightforward investigating the signature matrix (table 1). One can note that the Boolean signature vectors of a thermal detector and of a hydraulic detector are different. Consequently, the faults that affect them are isolable.

With a bond graph approach, this is explained by the fact that there is no causal loop between a hydraulic detector and a thermal one for the simple reason that only the hydraulic energy can influence thermal energy. □

**Corollary 2**. *Using a well placed thermal sensor, the set of thermal actuators $u_T$ and the set of hydraulic sensors $y_H$ become monitorable.*

The proof is obvious and rises from table 1. The well placed thermal sensor must ensure the detectability of the thermal actuators. □

**Corollary 3**. *By installing at least a hydraulic sensor, the* *set of the hydraulic actuators $u_H$ and the set of the thermal sensors $y_T$ become monitorable.*

The proof is obvious (see table 1). □

**Corollary 4.** *The set of hydraulic actuators $u_H$ is monitorable with the set of thermal actuators $u_T$ if one has at least one hydraulic sensor and one thermal sensor.*

The proof rises similarly from table 1 and the thermal detector was added to ensure the detectability of the thermal actuators. □

For actuators, physical components and sensors, their monitorability depends on the considered process. More particularly, let us consider the monitorability of the thermal sensors; a significant result can be stated:

**Theorem 2.** *Consider the thermal sensors in a well insulated thermofluid system in the under saturated case, all the faults that affect them are monitorable.*

**Proof.** Consider an accumulator *i* in a thermofluid circuit, its multienergy BG model is drawn on figure 1. $0_H$ and $0_T$ are respectively the hydraulic and the thermal 0-junctions. The thermal energy storage is given by equation (10).

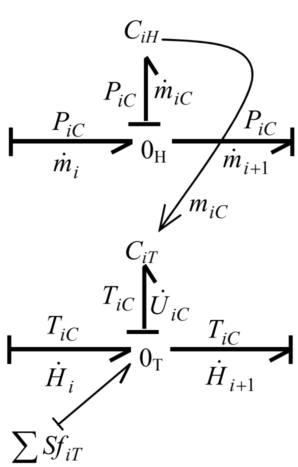


Fig. 1. BG model of an accumulator (integral causality).

$$\dot{x}_{iT} = \dot{U}_{iC} = \dot{H}_i - \dot{H}_{i+1} + \sum Sf_{iT} \qquad (10)$$

with:

- $\dot{H}_i$ is the inlet enthalpy flow (thermal flow by convection) acting on the accumulator *i*:
  $$\dot{H}_i = \dot{m}_i C_P T_{i-1C}$$
- $\sum Sf_{iT}$ is the sum of the thermal flow source variables by conduction or resulting from the external thermofluid sources (non installed in the circuit) acting on the *i* component.
- $\dot{U}_{iC} = \dot{m}_{iC} C_v T_{iC} = (\dot{m}_i - \dot{m}_{i+1}) C_v T_{iC}$ which represents the thermal energy stored in the accumulator.

$C_p$ and $C_v$ are respectively the specific heat at constant pressure and at constant volume.

It is supposed that the sensors have the label of the tanks on which they are installed (i.e., even if one does not have a sensor on tank 2, the detector on tank 3 is also $De_3$ ).

From equation (10), one would be able to determine $T_{iC}$ (the temperature of tank *i*) in terms of the temperature of an upstream tank (*upstream compared to the position of the accumulator i and taking into consideration the thermofluid flow direction*) using the recursive equation (11).

$$T_{iC} = \frac{\dot{m}_i C_p T_{i-1C} + \sum Sf_{iT}}{\dot{m}_{iC} C_v + \dot{m}_{i+1} C_p} \qquad (11)$$

To obtain the thermal ARRs, we consider an accumulator *j* equipped with a thermal sensor (measuring temperature), equation (10) allows us to write:

$$\dot{m}_{jC}.C_v.De_{jT} = \dot{m}_j.C_p.T_{(j-1)C} - \dot{m}_{j+1}.C_P.De_{jT} + \sum Sf_{jT} \qquad (12)$$

If the upstream accumulator (*j* -1) is equipped by a sensor, $T_{(j-1)C}$ is replaced by $De_{(j-1)T}$. Otherwise, $T_{(j-1)C}$ is deduced from the recursive equation (11): $T_{(j-1)C} = f(De_{kT})$, where $f$ is a function defined by equation (11) and $k$ the first accumulator equipped with a detector in the upstream position with respect to the accumulator (*j*-1).

By writing equation (11) from $i = (1...n)$ with $De_{0T} = 0$, we obtain the signature matrix given by table 1. While only the monitorability of thermal sensors is studied, the signatures of hydraulic sensors, sources and components are replaced by « * ». The obtained signature matrix is a lower triangular matrix and consequently all thermal sensors are monitorable.

Using a bond graph approach, this is justified by the presence of the special informational bonds (defined in [6]) preventing an accumulator from imposing its temperature on another accumulator being in the upstream position. □

Thermal actuators of thermofluid processes can be represented as thermal sources by conduction (heater) or by convection (thermal actuator of a thermofluid source). In process engineering, interesting results concerning the monitorability of thermal actuators can be stated:

TABLE II

SIGNATURES MATRIX OF FAULTS ON THERMAL SENSORS.

| | Thermal sensors | | | | | | | | | | Hydraulic sensors | Sources | Components |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $De_{1T}$ | | | $De_{(j-1)T}$ | $De_{jT}$ | $De_{iT}$ | $De_{(i+1)T}$ | | | $De_{nT}$ | | | |
| *Faults Signatures* | **1** | **0** | .. | .. | .. | .. | .. | .. | .. | **0** | * | * | * |
| | **1** | **1** | ⋱ | | | | | | | ⋮ | * | * | * |
| | **0** | **1** | ⋱ | ⋱ | | | | | | ⋮ | * | * | * |
| | ⋮ | ⋱ | ⋱ | ⋱ | ⋱ | | | | | ⋮ | * | * | * |
| | ⋮ | | ⋱ | **1** | **1** | ⋱ | | | | ⋮ | * | * | * |
| | ⋮ | | | ⋱ | **1** | **1** | ⋱ | | | ⋮ | * | * | * |
| | ⋮ | | | | ⋱ | **1** | **1** | ⋱ | | ⋮ | * | * | * |
| | ⋮ | | | | | ⋱ | **1** | ⋱ | ⋱ | ⋮ | * | * | * |
| | ⋮ | | | | | | ⋱ | ⋱ | ⋱ | **0** | * | * | * |
| | **0** | .. | .. | .. | .. | .. | .. | **0** | **1** | **1** | * | * | * |

**Theorem 3.** *A thermal detector placed at the* $i^{th}$ *accumulator isolates the set of faults affecting the thermal sources at upstream accumulators from the set of faults affecting the thermal sources at downstream accumulators (upstream and downstream compared to the position of the accumulator i and taking into consideration the thermofluid flow direction).*

The proof is obvious and rises from equation (12). □

**Example 1.** Consider a network of interconnected components in a thermofluid system under the form of a cascade of $n$ **C** (modeling accumulators) and of $n$ **R** (modeling valves) multiports. All tanks are supposed to be equipped by sensors. The purpose of this example is to illustrate theorems 2 and 3. The sub thermal BG model in derivative causality is given by figure 2. $Sf_1$, $Sf_2$,.., $Sf_m$ are the $m$ heating sources disposed on the $n$ tanks. The thick bonds are the special informational bonds.

According to [8], one knows that the thermal structure matrix can be written independently of the hydraulic power. To verify the two preceding theorems, one will generate thermal ARRs starting from the thermal structure matrix when preferential derivative causality is affected. The preferential derivative causality assignment puts all the thermal dynamic components in derived causality [13]. At the thermal level, equation (13) expresses mathematical relations from the junction structure.

$$\begin{bmatrix} T_{C1} \\ T_{C2} \\ \vdots \\ T_{Cn} \\ \dot{H}_1 \\ \dot{H}_2 \\ \vdots \\ \dot{H}_n \\ De_1 \\ De_2 \\ \vdots \\ De_n \end{bmatrix} = \left[\begin{array}{cccccccccccccccc} 0 & \cdots & \cdots & 0 & 1 & & & & 0 & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & 0 \\ \vdots & & & \vdots & & 1 & & & \vdots & & & & & & & \vdots \\ \vdots & & & \vdots & & & \ddots & & \vdots & & & & & & & \vdots \\ 0 & \cdots & \cdots & 0 & & & & 1 & 0 & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & 0 \\ -1 & 0 & \cdots & 0 & 0 & \cdots & \cdots & 0 & 1 & & & & & & & \\ -1 & -1 & \ddots & \vdots & \vdots & & & \vdots & 1 & 1 & 1 & & & & & \\ \vdots & & \ddots & 0 & \vdots & & & \vdots & 1 & 1 & 1 & 1 & 1 & & & \\ -1 & -1 & \cdots & -1 & 0 & \cdots & \cdots & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & \cdots & \cdots & 0 & 1 & & & & 0 & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & 0 \\ \vdots & & & \vdots & & 1 & & & \vdots & & & & & & & \vdots \\ \vdots & & & \vdots & & & \ddots & & \vdots & & & & & & & \vdots \\ 0 & \cdots & \cdots & 0 & & & & 1 & 0 & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & 0 \end{array}\right] \cdot \begin{bmatrix} \dot{H}_{C1} \\ \dot{H}_{C2} \\ \vdots \\ \dot{H}_{Cn} \\ T_1 \\ T_2 \\ \vdots \\ T_n \\ Sf_1 \\ Sf_2 \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ Sf_m \end{bmatrix} \tag{13}$$

with

$$T_i = \frac{\dot{H}_i}{\dot{m}_i \cdot C_p} \tag{14}$$

$$\dot{H}_{iC} = \dot{m}_{iC}.C_P.T_{iC} \tag{15}$$

Based on (13), (14) and (15), the $n$ ARRs are generated by doing some substitutions:

$$\begin{bmatrix} De_1 \\ De_2 \\ \vdots \\ De_n \end{bmatrix} = \begin{pmatrix} \frac{-1}{\dot{m}_1 C_p} & 0 & \cdots & 0 \\ \frac{-1}{\dot{m}_2 C_p} & \frac{-1}{\dot{m}_2 C_p} & \ddots & \vdots \\ \vdots & & \ddots & 0 \\ \frac{-1}{\dot{m}_n C_p} & \frac{-1}{\dot{m}_n C_p} & \cdots & \frac{-1}{\dot{m}_n C_p} \end{pmatrix} \cdot \begin{bmatrix} \dot{m}_{C1} C_p De_1 \\ \dot{m}_{C2} C_p De_2 \\ \vdots \\ \dot{m}_{Cn} C_p De_n \end{bmatrix} + \begin{pmatrix} \frac{1}{\dot{m}_1 C_p} & 0 & \cdots & \cdots & 0 \\ \frac{1}{\dot{m}_2 C_p} & \frac{1}{\dot{m}_2 C_p} & 0 & \cdots & 0 \\ \vdots & & & & \\ \frac{1}{\dot{m}_n C_p} & \frac{1}{\dot{m}_n C_p} & \frac{1}{\dot{m}_n C_p} & \frac{1}{\dot{m}_n C_p} & \frac{1}{\dot{m}_n C_p} \end{pmatrix} \cdot \begin{bmatrix} Sf_1 \\ Sf_2 \\ \vdots \\ \vdots \\ Sf_m \end{bmatrix} \tag{16}$$

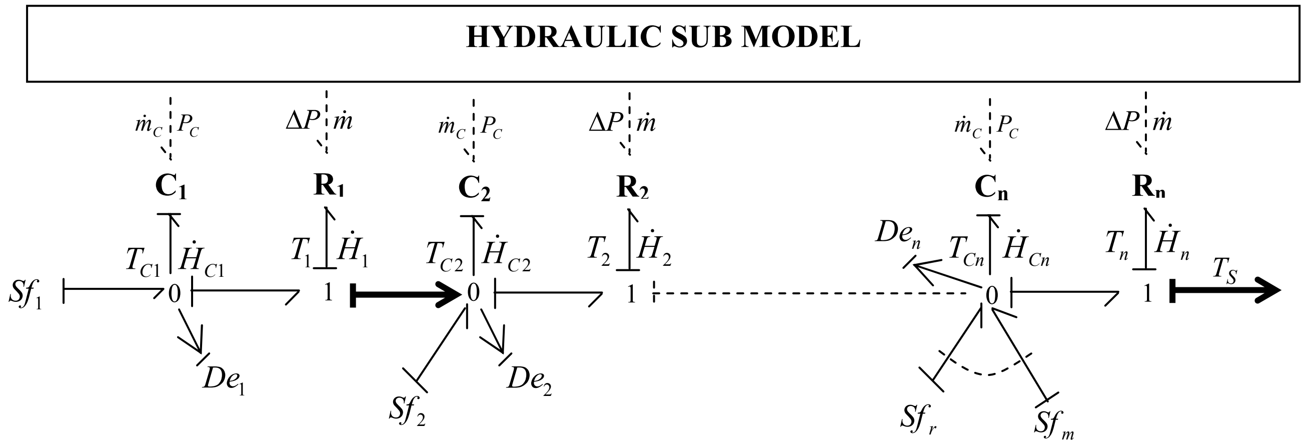

Fig. 2. BG model of a Network of Interconnected Components (in derivative causality).

We can thus deduce from equation (16) that all thermal detectors are isolable (theorem 2). However, this is not true for all sources, only some thermal sources are isolable. In fact, a thermal detector isolates the set of thermal actuators in the upstream position from the set of thermal actuators in the downstream position with respect to the tank where it is installed (theorem 3).

## III. CONCLUSION

Thermodynamic systems occur in many dangerous processes and need consequently an efficient monitoring system. The methods used in the literature consider only one type of faults (actuators, sensors or physical component) at a time. However, rather few results concern the monitoring of any type of components in process engineering. For a class of thermofluid processes, a diagnostic architecture for these sets of components is proposed, which is the main contribution of the paper. From now on, the diagnosability of any components can be deduced using the preceding results in the literature. In a second time, we have dealt more particularly with the sensors diagnosability problem and proved that all thermal sensors are monitorable which consequently drastically reduce the size of the problem.

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