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On the Thermoeconomic Approach to the Diagnosis of Energy System Malfunctions

Indicators to Diagnose Malfunctions: Application of a New Indicator for the Location of Causes

Andrea TOFFOLO, Andrea LAZZARETTO*
Department of Mechanical Engineering
University of Padova
Via Venezia, 1 - 35131 Padova, Italy
E-mail: andrea.lazzaretto@unipd.it

Abstract

Diagnosis procedures primarily aim at locating the control volumes where anomalies occurred. This is not a simple task, since the effects of anomalies generally propagate through the whole system and affect the behavior of several components. Some components may therefore present a reduced efficiency, although they are not sources of operation anomalies, due to non-flat efficiency curves. These induced effects are a big obstacle in the use of the thermoeconomic indicators for the search of the origin of the anomalies. As discussed in a brief overview of the several thermoeconomic indicators suggested in the literature, the reason for this inability is the focus on specific exergy consumptions as independent variables of the thermoeconomic model of the energy system. Instead, the real cause of the alteration of component behavior is the modification of its characteristic curve. Based on this concept, a new indicator measuring the alteration of the characteristic curve of the component affected by the operation anomaly is discussed and applied to the combined cycle power plant of the TADEUS problem.

Keywords: Thermoeconomics, energy system diagnosis, indicators, location of anomalies

1. Introduction

Diagnosis is a field of the research on energy systems devoted to the study of operation anomalies. These anomalies cause the actual performance of an energy system to differ from the expected (e.g. design) one, resulting in an increase of the amount of resources needed to obtain the same product, or, in more general terms, in a decrease of the overall efficiency.

Diagnosis is mainly aimed at *the detection of the overall efficiency reduction, the identification of the causes and the quantification of their effects*. The latter two goals are extremely difficult to achieve in most applications, since an anomaly occurring somewhere is likely to affect the performance of every single component of the system through the interaction of mass and energy streams and the intervention of the control system to restore the set-points or some fundamental operation parameters.

Diagnosis procedures rely on the comparison among two or more system working conditions. The most important ones are the "reference" operating condition, without any anomaly, and the "real" operating condition, characterized by an overall efficiency lower than that of the reference condition because of the presence of at least an anomaly.

The causes for performance variation in a component are usually classified into:

- *external* (e.g. due to variations of ambient condition and fuel quality),
- *intrinsic* (i.e. malfunctions due to component degradation or failures) and
- *induced*, defined as modifications in the operating point due to the interactions with the other components or to the intervention of the control system.

Since the most direct objective is to detect and locate intrinsic malfunctions, an effective

*Author to whom correspondence should be addressed *diagnostic procedure should be able to distinguish between intrinsic causes and induced effects*. However, the more complex the energy system, the higher the number of effects generated by the first cause, resulting in re-balances of mass and energy, with non-negligible contribution from the intervention of the control system.

In the thermoeconomic approach to diagnosis [Valero et al., 2004], exergy, not simply energy is used as the homogenous measure to define losses and efficiencies, and then to calculate costs (both exergetic and monetary). A thermoeconomic model of the energy system is needed to accomplish these tasks and has to be developed starting from the set of relationships describing mass/energy transformations/interactions in terms of thermodynamic quantities and from the set of independent variables of the whole energy system. A simple thermodynamic model is not enough, and a set of higher-level relationships has to be defined, deriving from the productive purpose of each sub-system (generally coinciding with a component) and the resources needed to obtain it. The graphical representation of these relationships is called "productive structure", which results in a set of flows, representing resources (fuel), products, by-products and energetic residues of the components, all expressed in terms of exergy.

All thermoeconomic approaches to the diagnosis of malfunctions in the literature (Valero et al., 1990, Lozano et al., 1994, Reini et al., 1995, Stoppato and Lazzaretto, 1996, Torres et al., 1999, Verda et al., 2002) start from a productive model of the component (derived from the thermodynamic model (see e.g., Reini et al., 1995, Valero et al. 2002a, Valero et al. 2002b) having one exiting product and various entering resources. This choice allows specific consumptions of the resources to be defined as the ratio of the exergy associated with that resource to the exergy of the product. The need of introducing specific exergy consumptions derives from the assumption of considering the:

Effect of anomaly = variation of specific consumption of a resource entering the component.

The thermoeconomic model of a component is therefore based on exergy flows and specific exergy consumptions, which appear as simple multipliers of the exergy associated with these flows.

Note that, according to this idea, the effect of malfunction is strictly linked with the concept of "production", that is with the definition of component productive purpose (product). Although the authors think that subjectivity is to be reduced as much as possible, and in most of the components this can be done using the SPECO method [Lazzaretto, Tsatsaronis, 1996, 1999], flexibility in the definition of fuels and product still remains.

In reality:

Effect of anomaly = variation of the characteristic curve of the component generating the anomaly.

Accordingly, in (Toffolo, Lazzaretto, 2003) we suggest evaluating these effects through a generic "indicator" which measures the distance of the actual operating point from the characteristic curve in the reference conditions. An application to the TADEUS plant (Valero et al., 2002a) of this new criterion is presented in this work, after a discussion on strength and limitations of thermoeconomic indicators previously used in the literature.

2. Use of Exergetic and Thermoeconomic Indicators in Diagnosing Malfunctions

As mentioned above, the objectives of energy system diagnosis are the evaluation of the effects of component malfunctions and the detection of the anomalies generating the malfunctions. A discussion follows about the use of exergetic indicators in the literature for both purposes.

2.1 Exergetic and thermoeconomic indicators

It is apparent that exergy and derived indicators can be used profitably to evaluate "effects" of malfunctions. In fact, exergy depends on the thermodynamic variables mass, pressure and temperature, and as such, it is suitable to measure performance characteristics, which are intrinsically "effects" of the operating conditions of the system.

In (Stoppato and Lazzaretto, 1996) and in further works (Lazzaretto et al., 1997, 1998, Stoppato et al., 2001) the following indicators were considered to evaluate effects of malfunctions in the components: ΔI, $\Delta I/I$, $\Delta I_{\Delta k}$, $\Delta I_{\Delta P}$.

All these indicators measure a difference between the value of an exergetic variable in the actual operating state and in the reference conditions.

The irreversibility variations ΔI of components measure the effects of the malfunctions in terms of loss of potential work. Part of this loss is caused by a variation of component behavior while the remaining part is due to the propagation of induced effects through the productive chain. Since at constant production of the total plant the exergy balance gives:

$$\Sigma\Delta I_h = \Delta F_T \qquad (1)$$

each term ΔI_h can be interpreted as the "effect" of the malfunction in terms of "contribution" given by the component to the increase in fuel consumption of the total plant. In order to supply a clearer picture of the irreversibility changes in relative terms, this effect can be related to the absolute value of the irreversibilities in the reference conditions ($\Delta I_h/I_h$). After defining component fuels and product, irreversibility changes can also be subdivided into two terms (Valero et al., 1990), related to the variation of fuel consumption $(\Delta I_{\Delta k})_h$ or to the variation of product $(\Delta I_{\Delta P})_h$.

$$\Delta I_h = (\Delta I_{\Delta k})_h + (\Delta I_{\Delta P})_h = \Delta k_h P_h + (k_h - 1)\Delta P_h \qquad (2)$$

The term $(\Delta I_{\Delta k})_h$ corresponds to the fuel variation in the component (at constant product) associated with the variation in the unit exergy consumption (k), whereas the term $(\Delta I_{\Delta P})_h = (k_h - 1)\,\Delta P_h$ represents the fuel variation in the component (at constant k) associated with the variation of the Product (P). This subdivision is done to "isolate" and distinguish the con-tributions deriving from variations of Δk and ΔP.

2.2 "Fuel impact" formula as an indicator

A different evaluation of the "contribution" given by the malfunctioning component (the h-th one) to the variation of the total plant fuel consumption (ΔF_T), is given by the "Fuel impact formula". This formula was first suggested in (Valero et al., 1990) and further developed in (Torres et al., 1999, Lozano and Valero, 1993, Reini, 1994). A summary discussion about its developments was presented in (Valero et al., 2002b).

In a productive structure represented by components having a single product and one or more entering resources (fuels), the fuel impact formula is expressed in finite terms as:

$$\Delta F_T = \sum_{h=1}^{n}\left(\sum_{j=0}^{n} k^*_{Pj}\Delta k_{jh}\right)P_{h_{ref}} + \sum_{h=1}^{n} k^*_{P_h}\Delta P_{e_h} \qquad (3)$$

where $P_{h_{ref}}$ is the product of the h-th component in the reference condition, $k^*_{P_j}$ is the unit exergetic cost of the product P_j of the j-th component which enters as resource (E_{jh}) in the h-th one, and Δk_{jh} is the variation between reference and operating conditions of the unit exergetic consumption of this resource due to the malfunction. ΔP_{e_h} is the variation of the overall plant production between reference and operating conditions due to the h-th component.

To facilitate the discussion, let us consider the case of constant overall production. In this case, equation (3) takes the form

$$\Delta F_T = \sum_{h=1}^{n}\left(\sum_{j=0}^{n} k^*_{Pj}\,\Delta k_{jh}\right)P_{h_{ref}} \qquad (4)$$

where the term

$$\Delta F_h = \sum_{j=0}^{n}\Delta k_{jh}\,P_{h_{ref}} \qquad (5)$$

corresponds to the "local" variation of fuel consumption ("local" fuel impact) in the h-th component. This variation is "transformed" into a variation of fuel consumption of the total plant ("total" fuel impact) by multiplying by the unit exergetic costs of each resource. ΔF_h is called "*endogenous irreversibility*" or "*malfunction*" MF_h in the matrix representation of the contributions to the total fuel impact suggested in (Torres et. al., 1999), and also coincides with the fraction $\Delta I_{\Delta k,h}$ of the h-th component irreversibility change ΔI_h. The sum of "*exogenous irreversibility*" or "*dysfunction*" DF_h terms in (Torres et. al., 1999), which are the remaining part of ΔI_h, coincides therefore with the fraction $\Delta I_{\Delta P,h}$.

In the same paper, the term

$$\Delta F_{T,h} = \sum_{j=0}^{n} k^*_{Pj}\,\Delta k_{jh}\,P_{h_{ref}} \qquad (6)$$

is called cost of malfunction, and represented as MF^*_h, so that

$$\Delta F_T = \sum_{h=1}^{n}\left(\sum_{j=0}^{n} k^*_{Pj}\,\Delta k_{jh}\right)P_{h_{ref}} = \sum_{h=1}^{n} MF^*_h \qquad (7)$$

2.3 Advantages of a "fuel impact" indicator

The fuel impact formula was originally developed to allocate in the only malfunctioning component all the effects of malfunctions, interpreted as "variations of *k*". In fact, the basic idea behind this formulation is the implicit association of malfunctions with variations of the specific consumption of the resources. Therefore,

specific consumptions (k) are implicitly considered as the only free variables of an exergoeconomic model of the system.

As an example of the potentiality of the fuel impact formula, a simple system made up of three components (A, B, C) having a linear structure, and constant values of k is considered (*Figure 1*). If a malfunction occurs in the downstream component (C), it does not affect the values of *k* for the resources entering A and B (*Figure 2*); so, the term $\Delta F_{T,h}$ (equation 6) is non-null, and equal to the variation in the fuel consumption of the total system for the only malfunctioning component (C), whereas it is null for the other two components (A, B). Thus, using $\Delta F_{T,h}$ as the indicator of the malfunction, it appears that the malfunctioning component contributes completely to the variation of the total plant fuel consumption. Conversely, the irreversibility variations are, in general, non-null for all the three components. Thus, if the ΔI_h associated with a specific component is interpreted as the contribution given by this

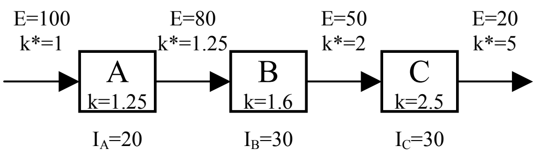

Figure 1. Reference state

component to the total system fuel variation (equation 1), it appears that all components contribute to it, not only the malfunctioning one. The advantages in having indicators which "isolate" the effects of malfunction in the only malfunctioning component are obvious when using this indicators in searching the causes of malfunction.

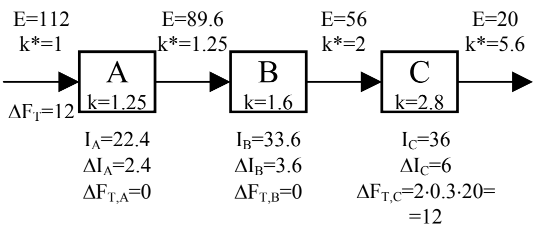

Figure 2. Anomaly in C – no induced effect

2.4 The problem of induced variations in the specific consumptions in non-malfunctioning components

The fuel impact term ($\Delta F_{T,h}$) associated with the h-th malfunctioning component and calculated with equation (6) is strictly equal to the total plant fuel variation only when the perturbation in the h-th component leaves the product of the component (P_h) and the exergetic cost $k^*_{P_j}$ of the *j-th* resource (E_{jh}) unchanged. This is equivalent to having the rest of the system outside component boundaries unchanged or, in other words, to disregarding any induced effect. This does not happen in the real operation since $k^*_{P_j}$, P_h and $k_{j,h}$ all depend on the set of independent variables of the system, and the variation of one of them, caused by an anomaly, results, in general, in a variation of $k_{j,h}$ and in variations of $k^*_{P_j}$ and P_h as well (*Figure 3*). In the calculation of the term $\Delta F_{T,h}$, the hypothesis of keeping $k_{j,h}$ and P_h constant derives from considering $k_{j,h}$ as the only free variables of the system (see Section 2.3). Since each of them depends only on the set of independent variables of the single components $\{\tau_h\}$, these have to be considered disjoint under this hypothesis. Thus, if a malfunction causes a variation $\Delta k_{j,h}$ in the j-th resource (E_{jh}) of the h-th component, this variation is supposed to act only on the h-th component, generating a variation $\Delta k_{j,h}P_h$ of its fuel ("local impact") and a variation $\Delta F_{T,h}= k^*_{P_j}\,\Delta k_{j,h}P_h$ of the fuel consumption of the total plant ("total impact").

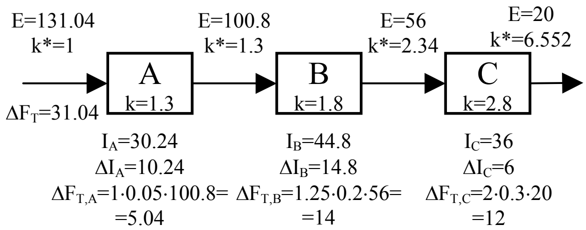

Figure 3. Anomaly in C - induced effects in A and B

Conversely, when a variation $k_{j,h}$ occurs in the real operation, the relation of dependence among $k_{j,h}$, P_h and $k^*_{P_j}$ is likely to result in "induced" variations of the specific consumptions in some of the other components, because some of the thermodynamic variables belong to more than one set $\{\tau_h\}$. Let us consider for example the simple system in *Figure 3*, having a linear structure, in which the malfunction occurs in component C. This malfunction is supposed to modify the ratio between product and fuel in one or both of the other components (A, B). Accordingly, also the specific consumption of resources varies in A and B. In such conditions the application of the fuel impact formula does not supply clear results as intrinsic, and induced effects appear at once. The presence of internal loops within system boundaries, both due to recirculation of matter/energy or to the effect of the control system, increases the probability of having variations of k in components indirectly affected by the original malfunction. To overcome these drawbacks of the fuel impact formula, as suggested in (Stoppato and Lazzaretto, 1996)and further works (Lazzaretto et al., 1997, 1998, Stoppato et al., 2001), it was proposed to *consider the induced variations in the same way* *as the intrinsic variations*. Thus, whatever the component originating the malfunction, an "impact term" arises in those components showing a variation of specific consumption, i.e. a single malfunction originates more than one impact term ($\Delta F_{T,1}$, …, $\Delta F_{T,h}$,... $\Delta F_{T,n}$). All these components contribute to the total plant fuel variation, not only the malfunctioning one, a sort of "principle of effect superimposition" being applied. The contribution to the variation of the total plant fuel consumption given by the components affected by only induced variations of specific consumption is

$$\Delta F_T^{induced} = \sum_{l \neq h} \left(\sum_{j=0}^{n} k_{Pj}^* \ \Delta k_{jl} \right) P_{l_{ref}} \tag{8}$$

Accordingly, the variation of the total plant fuel consumption ("total" fuel impact) is

$$\begin{aligned} \Delta F_T &= \Delta F_{T,h} + \Delta F_T^{induced} \\ &= \sum_{j=0}^{n} k_{Pj}^* \ \Delta k_{jh} \ P_{h_{ref}} + \sum_{l \neq h} \left(\sum_{j=0}^{n} k_{Pj}^* \ \Delta k_{jl} \right) P_{l_{ref}} \end{aligned} \tag{9}$$

The value of ΔF_T obtained from equation (9) may differ more or less from the true (measured) value of ΔF_T depending on all the introduced approximations, as previously discussed.

2.5 Use of exergetic and thermoeconomic indicators in the search for the origins of malfunctions

All the exergetic and thermoeconomic indicators presented in Section 3 measure the "effects" of malfunctions in different ways, while all being formulated to allocate the irreversibility losses among components. In (Stoppato and Lazzaretto, 1996)it was proposed to use these indicators to detect causes of malfunction starting from the simple idea that the components showing the highest values of a particular indicator should be those in which the malfunction was originated. According to this idea, the components were ranked in decreasing order of each of these indicators. This technique has shown to give only a probable indication of the components in which a single malfunction is originated and, in case of more malfunctions, does not permit realizing whether the malfunctions originate in one or more components. Several plants with different levels of complexity were then studied (Lazzaretto et al., 1997, 1998, Stoppato et al., 2001) to verify the reliability of the approach. In specific cases, particularly when the system is characterized by a low level of interaction among components, the method has proved to be effective, but in general it does not supply clear indications on the origin of malfunction. The reason for these results is the *inability of the approach to distinguish between intrinsic and induced effects*. In fact, exergetic indicators depend on the set of thermodynamic variables τ of the system, which in turn depend on component interactions; therefore the values of the indicators cannot be considered unlinked with these interactions. The same problem arises when the "Fuel Impact Formula" is used to detect the components affected by operation anomalies. In fact, the "local impacts" due to specific consumption variations ($\Delta I_{\Delta k}$ or MF see equation 2) are considered as "independent" effects, disregarding the fact that part of these terms is due to induced effects caused by variations of products or specific consumptions in other components. Differences between exergetic and thermoeconomic indicators and the Fuel Impact Formula in the search for the origin of malfunctions have been discussed in (Stoppato and Lazzaretto, 1996).

3. A New Thermoeconomic Approach to Detect Anomalies

All the presented approaches to thermo-economic diagnosis of malfunctions more or less implicitly consider the exergetic variables as the independent variables of the analysis. A different methodology is suggested in (Toffolo and Lazzaretto, 2003), which considers *exergetic variables as a measure of performance and thermodynamic variables τ as the "true" independent variables of the system*. The starting point of this methodology is the definition:

Operation anomaly = modification of the component characteristic curve due to degradation or failure, resulting in an intrinsic malfunction,

where the characteristic curve is the set of relationships among component variables (e.g. machine performance maps, heat exchanger ε-NTU model, etc.).

Operation anomalies cause the system operating condition to move from the original state (reference) to a new state (real). In the latter, all non-malfunctioning components continue to operate on their original (reference state) characteristic curve, but, in general, in a different point of this curve, usually but not necessarily characterized by a degraded efficiency. In fact, as a consequence of an operation anomaly in a component, it may happen that a different component of the system:

1) is not affected by the anomaly and therefore its working point remains unchanged (as in the reference state);

2) undergoes an induced malfunction which modifies its working point but cannot alter its characteristic curve; the working point moves on this curve and the efficiency varies accordingly.

Conversely, the working point of the malfunctioning components does not belong any more to their original characteristic curve.

Therefore an effective method to locate the components affected by operation anomalies is to verify whether the real working point still belongs to the reference characteristic curve.

A direct observation of the characteristic curves, when they are available for all components, easily solves the problem. Otherwise, the changes occurring between reference and real operating conditions are to be analyzed in order to verify whether the operating point of the component moves back to the original performance by "virtually restoring" the operating conditions of the reference state. The idea is to "bring back" the operating point along the path imposed by the characteristic curve in the reference condition: if an anomaly has caused an alteration of the characteristic curve, the point will not coincide with the reference one, showing an intrinsic malfunction in the component. Conversely, if the point returns to the reference operating condition, the component has only been affected by induced malfunctions.

The mathematical tool to perform this comparison is an "indicator" expressed as:

$$\begin{aligned}\text{indicator} &= \Delta\text{performance} - \left(\Delta\text{performance}\right)_{\text{calculated}} \\ &= \Delta\text{performance} - \sum_i \left(\frac{\partial\text{performance}}{\partial\text{variable}_i}\right)_{\text{reference}} \Delta\text{variable}_i\end{aligned} \tag{10}$$

where "performance" is a performance measure dependent on a set of component independent variables "variable$_i$", and the variation Δ is evaluated between the real and the reference operating conditions. The derivatives $(\partial\text{performance}/\partial\text{variable}_i)_{\text{reference}}$ represent the relation between "performance" and "variable$_i$" imposed by the characteristic curve, and are evaluated in the reference operating condition.

This indicator shows the residual value of "performance" when the effects of the variations of "variable$_i$" are removed: if the component is not responsible for the anomalies and these effects are induced by the productive chain (i.e. by the relationships existing among the thermodynamic variables generated by component interaction) or by control system action, the indicator will show a null value (neglecting the approximation introduced with the linearization of the characteristic curve); if, conversely, the indicator shows a residual difference of "performance", it is not possible to restore the reference operation conditions in the component since the characteristic curve has been altered because of the anomaly.

The use of exergetic variables as the "performance" measure is indeed recommended since they include information related to mass and energy flows in a single quantity, exergy, directly linked to the efficiency of the energy conversion process. In principle, various exergetic variables can be used. The simpler choice seems however to be the component irreversibility I, which depends on the system state and is defined in a unique way. Moreover,

Since malfunction always alters the component characteristic curve in a negative way, a strictly positive value of the "indicator" is guaranteed in case of intrinsic malfunction.

On the other hand, the natural choice for a set of independent "variable$_i$" is among the thermodynamic variables of the component. Conversely, exergetic variables are not suitable to be used as "variable$_i$" because the synthesis of thermodynamic information that is so useful to define component performance becomes a handicap from the mathematical point of view in modeling the relationship among component thermodynamic variables defined by the characteristic curves. In fact, when exergy or any other exergetic variable are used as component independent variables, the same variation of one "variable$_i$" can be obtained through different variations of the associated thermodynamic variables, resulting in turn in different effects on component "performance". In other words, a univocal relationship between the variations of the exergetic variable considered as "variable$_i$" and component "performance" does not exist. A productive structure considering the mechanical, thermal and chemical exergy flows still does not provide a sufficient number of variables to cover component degrees of freedom. A univocal relationship could exist if mass flow rates and specific exergy components were used as "variable$_i$". However, besides the unavoidable complication of this approach in comparison with the one using thermodynamic variables τ, an ambiguity also exists on the choice of the paths to be followed in the evaluation of the thermal and mechanical components of exergy, particularly when phase changes are involved (Tsatsaronis et al., 1990).

Recently, a thermoeconomic modelization of a component which uses the derivatives $\partial k/\partial E$ to filter the effects of induced malfunctions in the fuel impact formula was proposed within a strategy aimed at locating causes of anomalies (Verda et al., 2002).

Different productive structures were studied to find the best to fit the actual component behaviour. Nevertheless, the authors concluded the analysis realizing that the loss of information associated with the use of thermoeconomic variables prevents mathematically solving the problem of locating the sources of anomalies starting from the evaluation of their effects.

4. Example of Application

The indicator presented in the previous section has been tested to locate the components affected by operation anomalies using the TADEUS problem (Valero et al., 2002a) as an example of application. The TADEUS plant is a combined cycle power plant made up of two gas turbines, two HRSGs and a steam turbine; details about the plant and the reference operating condition considered are given in the third part of this work (Verda et al., 2003). Three operating anomalies were introduced to alter the reference operating condition:

- erosion of the turbine in gas turbine A, causing decreased turbine efficiency and increased flow capacity;
- fouling of the high pressure super-heater in HRSG A, causing a decreased heat transfer between flue gas and steam;
- fouling of the air filter at compressor inlet in gas turbine A, causing a decrease of compressor inlet pressure.

The resulting real operating condition is provided in (Verda et al., 2003), as well.

Component irreversibility I_h was chosen as a measure of “performance”, and a set of component independent thermodynamic / control variables $\{\tau_h\}$ was chosen to be used as “variable$_i$”. Accordingly, the indicator expresses the residual irreversibility associated with a component when reference conditions are restored:

$$I_{res,h} = \Delta I_h - \sum_{i=1}^{size\{\tau_h\}} \frac{\partial I_h}{\partial \tau_{h,i}} \Delta\tau_{h,i} \qquad (11)$$

A non-null value of the residual irreversibility clearly indicates that the component is affected by an operation anomaly. The thermo-dynamic/control variables chosen for each component are shown in TABLE I. Note that outlet pressure is preferred to mass flow rate in the independent variable set of machines because it is easier to deal with this variable when the mass flow/pressure ratio characteristic is nearly vertical (compressor maps in particular).

The derivatives $\partial I_h / \partial \tau_{h,i}$ for the h-th component were calculated using a number of operating conditions, very close to the reference one, which were obtained varying the values of the independent variables $\{\tau_h\}$ using different combinations of control system parameters and/or external conditions, and/or introducing anomalies in other components.

Let the calculation of the derivatives $\partial I_h / \partial \tau_{h,i}$ for the HP steam turbine be considered as an example. The independent variables of this component are three (see TABLE I), therefore at least three operating conditions (op1, op2 and op3), not far from the reference one, are required for the calculation. The derivatives can then be determined using the system of equations in *Figure 4*.

TABLE I. COMPONENT INDEPENDENT VARIABLE SETS $\{\tau_h\}$

Component	$\{\tau_h\}$
Air filter	G_{gt0}, p_{gt0}, T_{gt0}, air humidity
Compressor	p_{gt1}, T_{gt1}, p_{gt2}, IGV angle, air humidity
Combustor	G_{gt2}, p_{gt2}, T_{gt2}, G_{gt10}, air humidity
Gas turbine	p_{gt3}, T_{gt3}, p_{gt4}, gas composition, air humidity, G_{gt6}, p_{gt6}, T_{gt6}, G_{gt7}, p_{gt7}, T_{gt7}, G_{gt8}, p_{gt8}, T_{gt8}, G_{gt9}, p_{gt9}, T_{gt9}
HP superheater	G_{g13}, p_{g13}, T_{g13}, G_{g9b}, p_{g9b}, gas composition
HP evaporator	G_{g14}, p_{g14}, T_{g14}, G_{g8}, p_{g8}, gas composition
LP superheater	G_{g15}, p_{g15}, T_{g15}, G_{g11}, p_{g11}, gas composition
HP economizer	G_{g16}, p_{g16}, T_{g16}, G_{g6}, p_{g6}, T_{g6}, gas composition
Circulation pump	G_{g5}, p_{g5}
LP evaporator	G_{g17}, p_{g17}, T_{g17}, G_{g3}, p_{g3}, gas composition
LP economizer	G_{g18}, p_{g18}, T_{g18}, G_{g1}, p_{g1}, T_{g1}, gas composition
Extraction pump	G_{st6}, p_{st6}
HP steam turbine	p_{st1}, T_{st1}, p_{st2}
LP steam turbine	p_{st4}, T_{st4}, p_{st5}
Condenser	G_{st5}, p_{st5}, h_{st5}

$$\begin{bmatrix} (p_{st1})_{op1} - (p_{st1})_{ref} & (T_{st1})_{op1} - (T_{st1})_{ref} & (p_{st2})_{op1} - (p_{st2})_{ref} \\ (p_{st1})_{op2} - (p_{st1})_{ref} & (T_{st1})_{op2} - (T_{st1})_{ref} & (p_{st2})_{op2} - (p_{st2})_{ref} \\ (p_{st1})_{op3} - (p_{st1})_{ref} & (T_{st1})_{op3} - (T_{st1})_{ref} & (p_{st2})_{op3} - (p_{st2})_{ref} \end{bmatrix} \begin{bmatrix} \dfrac{\partial I}{\partial p_{st1}} \\ \dfrac{\partial I}{\partial T_{st1}} \\ \dfrac{\partial I}{\partial p_{st2}} \end{bmatrix} = \begin{bmatrix} I_{op1} - I_{ref} \\ I_{op2} - I_{ref} \\ I_{op3} - I_{ref} \end{bmatrix}$$

Figure 4. System of equations for the calculation of $\partial I_h / \partial \tau_{h,i}$ for the HP steam turbine

The residual irreversibilities $I_{res,h}$ calculated for each component of the TADEUS plant are shown in TABLE II. The ratios $I_{res,h}/|(\Delta I_h)_{calc}|$ are also reported in TABLE II, because they are more effective in indicating malfunctioning components than $I_{res,h}$, which is expressed in absolute terms, due to the approximation introduced with a linear representation of component characteristic curves through the derivatives $\partial I_h / \partial \tau_{h,i}$. All the three com-ponents affected by operation anomalies are correctly identified by the indicator. The approximation error in the calculation of component irreversibilities ΔI_h through the derivatives of I with respect to component independent variables is within 1% for the other (non-malfunctioning) components

TABLE II. LOCATION OF COMPONENTS AFFECTED BY OPERATION ANOMALIES USING $I_{res,h}/ |(\Delta I_h)_{calc}|$

Component		$I_{h,ref}$ [kW]	$I_{h,real}$ [kW]	ΔI_h [kW]	$(\Delta I_h)_{calc}$ [kW]	$I_{res,h}$ [kW]	$I_{res,h}/|(\Delta I_h)_{calc}|$ (%)
Air filter	GT A	330.8185	422.4305	91.61193	6.743116	84.86882	**1258.599**
Compressor	GT A	17117.22	17924.31	807.0915	810.4912	–3.399685	–0.419
Combustor	GT A	116867.1	118082.8	1215.709	1219.758	–4.049036	–0.332
Gas turbine	GT A	18663.58	19908.56	1244.981	–66.87821	1311.86	**1961.565**
Air filter	GT B	330.8185	335.9091	5.090563	5.090563	0	0.000
Compressor	GT B	17117.22	17759.75	642.5286	647.824	–5.295481	–0.817
Combustor	GT B	116867.1	117618.3	751.1834	755.354	–4.170641	–0.552
Gas turbine	GT B	18663.58	18968.73	305.145	306.0971	–0.952044	–0.311
HP SH	HRSG A	2472.524	2553.024	80.49927	69.97398	10.52529	**15.041**
HP EV	HRSG A	6496.152	6647.924	151.7712	150.8108	0.96036	0.637
LP SH	HRSG A	218.0382	222.3338	4.295554	4.278908	0.016646	0.389
HP ECO	HRSG A	1002.965	1027.595	24.63046	24.57037	0.060089	0.245
Circ. pump	HRSG A	43.2195	44.94002	1.720521	1.705857	0.014663	0.860
LP EVAP	HRSG A	1207.084	1221.466	14.38186	14.48797	–0.106111	-0.732
LP ECO	HRSG A	197.8653	188.5609	–9.304422	–9.261083	–0.043339	–0.468
HP SH	HRSG B	2472.524	2435.097	–37.42739	–37.2079	–0.219495	–0.590
HP EVAP	HRSG B	6496.152	6414.835	–81.31695	–80.53085	–0.786095	–0.976
LP SH	HRSG B	218.0382	225.1453	7.107044	7.07927	0.027774	0.392
HP ECO	HRSG B	1002.965	1016.749	13.78446	13.79832	–0.013861	–0.100
Circ. pump	HRSG B	43.2195	43.91774	0.698234	0.696539	0.001695	0.243
LP EVAP	HRSG B	1207.084	1248.123	41.03874	40.65056	0.388172	0.955
LP ECO	HRSG B	197.8653	184.0858	–13.77952	–13.70156	–0.077956	–0.569
Extr. pump	ST	16.80282	17.25288	0.45006	0.445648	0.004412	0.990
HP turbine	ST	6109.1	6185.543	76.44247	76.14716	0.295308	0.388
LP turbine	ST	11663.46	11837.39	173.9307	173.8452	0.085466	0.049
Condenser	ST	27730.66	28435.3	704.6424	704.0481	0.594375	0.084

5. Conclusions

In the recent past, a lot of research has been done to exploit the potentialities of exergetic variables to solve the problems in energy system diagnosis. The reasons of the main advantages and drawbacks of these approaches, based on the use of exergetic variables as independent, are discussed and clarified in this work. The use of exergy demonstrated however to be effective if the actual links among thermodynamic variables, which determine component interactions, are taken into account in the analysis. To this end, the application of an innovative criterion based on a new “exergetic indicator” is presented, which properly considers the true thermodynamic relationships among component variables. As such, it guarantees the “certainty” of the answer to the problem of the search of malfunctions in terms of methodological approach, uncertainties being limited to the inaccuracies of the calculations.

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