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Case Study Open Access

On Energy Reconciliation Diagnose and Their Malfunction: A Proposal of Routes Corrections, Case of Study: Geothermal Power Cycle

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Abstract

In actual energy process in operation, the appearance of Malfunctions that affect the performance and efficiency of the system must be taken care of and evaluated. Previously, in this article, a method to evaluate Malfunctions in energy processes in operation has been presented/described. This method Consists of an evaluation of the current test state (AS) of an energy process and a comparison to a guaranteed reference state (on/off design) (RS), reconciling malfunction by malfunction from the AS to the RS. Moreover, derived from different observations of the scientific community related to the path of reconciliation and order to assess malfunctions. In this article, these are answered and an analysis is made comparative of the reconciliation to fixed demand of power and to fixed load of mass flow and it is possible to make a comparative of different models of reconciliation. Finally the route of correction of Malfunctions is proposed, based on the most habitual practice in the energetic processes, to be implemented in the energy diagnosis reconciliation models in general. The analysis and results are developed for a Rankine organic geothermal steam cycle

Keywords: Thermoeconomic diagnosis; Dysfunctions; Thermal regime

Nomenclature

$HR: Economic Heat Rate ($/kWh)

W: Mechanical Power (kW)

m: Mass flow (kg/s)

H: enthalpy (kJ/kg)

HR: Heat Rate (-)

M: Independent Variables

P: Pressure (Bar)

T: Temperature (°C)

Greek letters

Δ: Difference

ε: Component Efficiency (-)

η: Cycle Efficiency (-)

Subindices

0: Environmental Conditions

1: Main steam

2: Turbine exhaust

23: Condenser

3: Pump suction

4: Evaporator Input

41: Evaporator

C: Cold Fluid

D: Design State

Evap: Evaporation

Exp: Expander

H: Hot Fluid

in: inlet

iso: Isoentropic

Pp: Pump

R: Actual test status

f: Function

Introduction

In all thermoelectric plants there are a number of causes that affect the performance (or thermal regime) and production, such as: erosion, sediment, breakage, deviation to control, etc. In this sense, most manufacturers and designers of thermoelectric cycles offer "graphic methods" of correction for a limited number of causes that impact the process. This method has disadvantages due to the hours of analysis it requires and the lack of other causes to complete a diagnosis.

On the other hand, some research groups have contributed methods for the diagnosis of anomalies in plants, based on exergoeconomics [1-6]. However, the resulting analytical models are complex and in some cases analytical approaches such as homogeneity and numerical linearity, among others, are required to solve these models; leaving to demonstrate the precision and feasibility of implementation in plant.

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With the aim of providing an immediate and accurate response in the diagnosis of thermoelectric power plants in operation, this paper presents a methodology that allows timely reporting and assessment of deviations from the Thermal Regime (defined in eqn. (1)) and the power for causes separated.

$$HR=\frac{1}{\eta}=\frac{\text{Input Power}}{\text{Power Generated}} \tag{1}$$

The methodology consists of designing a modular numerical-analytical simulator that reconciles from a "test state" of operation to an optimal "reference state".

Methodology

The reconciliation diagnosis methodology of the Heat Rate and Cycle Efficiency consists of seven important steps:

1) Definition of the functional structure of the plant.
2) Definition of the analytical model for the reproduction of thermal and thermoeconomic balances (State of Reference).
3) Performance Test (Test Status).
4) Declaration of free variables (anomalies).
5) Definition of reconciliation module.
6) Data Reconciliation.
7) Online Implementation.

In this article, the entire methodology will not be described in detail since it is published earlier [1].

Declaration of free variables

Next, the declaration step of free variables (anomalies or malfunctions) will be described, as well as defining the two objective functions to be found by means of a simulator: The Heat Rate and the Efficiency of the cycle as a function of independent variables ($M_1 \ldots M_m$):

$$\eta=\eta\left(M_1,M_2,\ldots,M_m\right) \tag{2a}$$

$$HR=HR\left(M_1,M_2,\ldots,M_m\right) \tag{2b}$$

Where M_i represents the Malfunctions that impact the Heat Rate and the Efficiency of the cycle, respectively, when an anomaly occurs in the model.

Classification of abnormalities

The anomalies that impact the Heat Rate and the Efficiency of the cycle are defined as external and internal, as described in Figure 1.

To make the comparison between the CURRENT TEST STATUS and the REFERENCE STATUS, a reconciliation is carried out, using a module (described in the algorithm of Figure 2) in which the Thermal

	CATEGORY	DESCRIPTION
EXTERNAL	ENVIRONMENTAL CONDITION	• Variation of environmental conditions (P_0, T_0, humidity).
	FUEL QUALITY	• Variation in fuel quality (PCS, PCI, composition).
INTERNAL	INTRINSIC	• Presence of anomalies (intrinsic malfunctions).
	INDUCED	• Anomalies generated by the dependence of a component on other components (induced malfunctions).
	CONTROL SYSTEM	• Intervention of the control system (deviations in intensive and extensive properties).

Figure 1: Classification of the anomalies in power cycles.

$$\begin{aligned}
&MODULE\ RECON(M_1,M_2,\ldots M_m : HR,\eta)\\
&\quad HR=HR(M_1,M_2,\ldots M_m)\\
&\quad \eta=\eta(M_1,M_2,\ldots M_m)\\
&END\\
\\
&CALL\quad RECON\ (M_{ST1.1,T},M_{ST1.2,T},\ldots M_{GT2.13,T} : HR_T,\eta_T)\\
&CALL\quad RECON\ (M_{ST1.1,R},M_{ST1.2,T},\ldots M_{GT2.13,T} : HR_{ST1.1},\eta_{ST1.1})\\
&\quad \Delta HR_{ST1.1}=HR_T-HR_{ST1.1}\\
&\quad \Delta\eta_{ST1.1}=\eta_T-\eta_{ST1.1}\\
&CALL\quad RECON\ (M_{ST1.1,R},M_{ST1.2,R},\ldots M_{GT2.13,T} : HR_{ST1.2},\eta_{ST1.2})\\
&\quad \Delta HR_{ST1.2}=HR_{ST1.1}-HR_{ST1.2}\\
&\quad \Delta\eta_{ST1.2}=\eta_{ST1.1}-\eta_{ST1.2}\\
&\quad \bullet\\
&\quad \bullet\\
&\quad \bullet\\
&CALL\quad RECON\ (M_{ST1.1,R},M_{ST1.2,R},\ldots M_{GT2.13,R} : HR_R,\eta_R)\\
&\quad \Delta HR_{GT2.13}=HR_{GT2.13}-HR_R\\
&\quad \Delta\eta_{GT2.13}=\eta_{GT2.13}-\eta_R
\end{aligned}$$

Figure 2: Outline of the declaration of the MODULE and CALL.

Regime and power are determined by means of mathematical models used by the simulator, re-accommodating the free variables.

Once the module is created, a call is made (CALL) to initially evaluate the test status. Then each test parameter is replaced successively by a reference one, until all the anomalies are replaced. In other words, it is equivalent to evaluating eqn. (2) in terms of free variables M_i, repositioning each term from its test value to its reference value, and in each step calculating the difference ΔHR yΔη, respectively. Once ΔHR has been obtained, the cost per anomaly can be determined.

Justification

However, this precisely mentioned sequence has been questioned in scientific forums, hence the need to clarify which is the correct route or routes for the reconciliation of malfunctions in an advanced energy system. For this a basic case will be presented and a reconciliation will be made with different order of the malfunctions, to fixed power demand and to fixed charge of mass flow, to set a common basis and thus establish a route more congruent to what happens in energy process plants. The correction of each of the Malfunctions for the Reconciliation Modules is represented by the following four paths:

i. From the values of Design to the Real values.

ii. Changing only one at a time, from the Design values to the Real values.

iii. Changing only one at a time, from the Real values to the Design values.

iv. From the Real values to the Design values.

Case Study

To justify the correct routes for the Energy Reconciliation Model we worked with the simulation of a Basic Organic Rankine Cycle which is fed by a geothermal deposit and is schematized in Figure 3. In Table 1 the characteristic points are described of the system and its thermodynamic properties design conditions.

A thermodynamic model has been developed, in which the properties of the working fluid have been obtained through the EES software.

To develop the model that allows carrying out the analysis, the following assumptions have been considered:

- Stationary regime in all system components.
- Heat losses in the pipes are neglected.
- The constant temperature of the geothermal reservoir is 150°C.
- The hot fluid temperature is equal to the geothermal reservoir.
- Constant supply temperature of cold fluid of 20°C
- There is a ΔT of 10°C between the heat exchangers and the working fluid.
- Constant pressure drop in the evaporator of 7%.

Natural gas price of $4,154 USD/GJ (Reference average price in Mexico, October 2018).

Characteristic point	Description	T (°C)	P(Bar)	h (kJ/kg)	Power (kW)
1	Main steam	135	21.27	502.4	n/a
2	Turbine exhaust	79.28	2.496	473.1	n/a
3	Pump suction	35	2.446	245.8	n/a
4	Evaporator Input	36.25	22.76	248	n/a
5	Turbine power	n/a	n/a	n/a	500
6	Condenser	40	2.496	Change Phase	4198
7	Pump	n/a	n/a	n/a	40.8
8	Evaporator	125	21.27	Change Phase	4698

Table 1: Characteristics and thermodynamic properties under system design conditions.

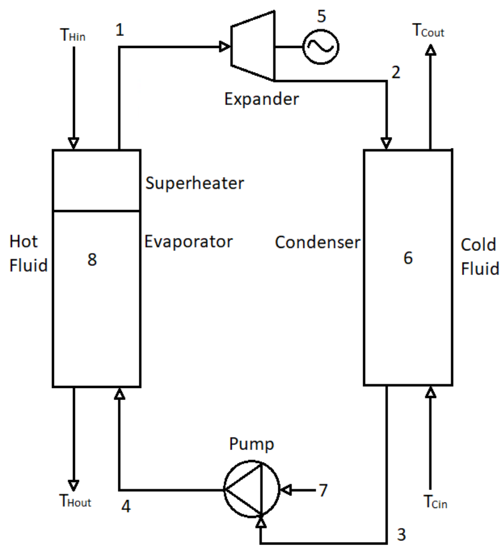

Figure 3: Scheme of the basic organic Rankine cycle fed by a geothermal deposit.

In this section we will describe the governing equations of a basic organic Rankine cycle fed by geothermal source energy source and also the modes of control and operation that this system will have, as well as the mathematical model of the case study.

The evaporator is the heat exchanger where the thermal energy transfer from a hot fluid to a working fluid takes place, with the objective that the working fluid makes a phase change from the liquid to the gaseous state at a constant temperature. In Figure 4, the behavior of both fluids inside the evaporator and superheater is shown, where the output of the working fluid has a ΔT of 10°C of the logarithmic average temperature of the hot fluid. The phase change of the working fluid takes place at 125°C, therefore, the pressure at point 1 of the cycle is obtained with the phase change temperature, then:

$$P_1=f(T_{Evap})$$

The temperature of point 1 is obtained with the sum of the evaporation temperature and an added superheat of 10°C to the working fluid, in order to ensure that only superheated steam enters the expander, then:

$$T_1=T_{Evap}+\text{Superheater} \quad (3)$$

The overall efficiency of the expansion process is defined as the division of the power obtained between the maximum power that could be obtained ideally, through an isentropic expansion, said efficiency has a value of 70%. The electrical power generated by the expander is 500 kW and is expressed as follows:

$$\dot{W}_{Exp}=\varepsilon_{Exp}\cdot\dot{m}\cdot(h_1-h_{2iso}) \quad (4)$$

The main function of the condenser in a thermal power plant is to be the cold focus or heat sink within the thermodynamic cycle, therefore, it serves to condense the steam after performing a thermodynamic work. In Figure 5, the behavior of both fluids inside the condenser is shown, where the output of the working fluid has a ΔT of 10°C of the logarithmic average temperature of the cold fluid. The phase change is generated isothermally at 40°C, therefore, the pressure at point 2 of the cycle is obtained with the phase change temperature in the condenser as shown:

$$P_2=f\left(T_{Cond}\right)$$

The process of expansion assumes adiabatic. The conditions at the output of the expander are calculated according to the following equation:

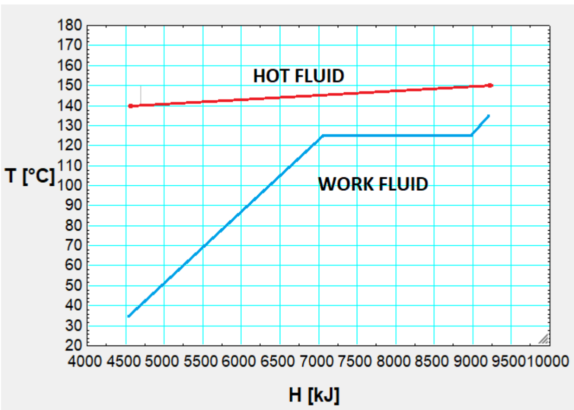

Figure 4: Behavior of fluids inside the evaporator.

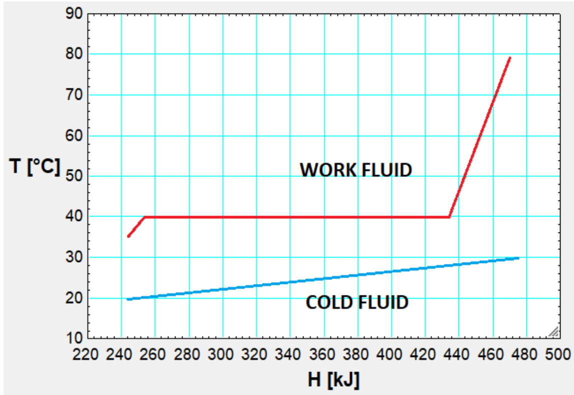

Figure 5: Behavior of fluids inside the condenser.

$$h_2=h_1-\frac{\dot{W}_{Exp}}{\dot{m}} \quad (5)$$

The working fluid must have a certain degree of subcooling at the inlet of the pump to avoid cavitation phenomena in it. Therefore, at the condenser outlet, a subcooling of 5°C is added to the working fluid. In the same way, a constant pressure drop of 2% is taken into account at the condenser outlet. Then, the temperature at point 3 would be represented as follows:

$$T_3=T_{Cond}-\text{Subcooling} \quad (6)$$

The pumping process is assumed to be isentropic. The overall efficiency of the pumping process is 70%. The overall efficiency of the pumping process, analogous to the overall efficiency of the expansion process, is defined as the division of the minimum power that could be consumed ideally, through an isentropic pumping process, on the electrical power consumed by the pump. The electrical power consumed by the pump is calculated according to the following equation:

$$\dot{W}_{Pp}=\frac{\dot{m}\cdot(h_{4iso}-h_3)}{\varepsilon_{Pp}} \quad (7)$$

To determine the performance of the system, in addition to the electrical power generated by the expander and the electrical power consumed by the pump, other dependent variables are defined. One of them is the net efficiency of the system which is defined as the division of the net electric power produced by the system on the thermal power captured by the system, represented as follows:

$$\eta=\frac{\dot{W}_{Exp}-\dot{W}_{Pp}}{\dot{Q}_{Evap}}\cdot 100 \quad (8)$$

We also use the Heat Rate as a performance variable, which is the measure of the performance of a thermoelectric power plant. It is the quotient between the thermal energy provided in the form of fuel and the electric energy generated.

$$\$HR=\frac{3600\cdot\dot{Q}_{Evap}}{\dot{W}_{Exp}-\dot{W}_{Pp}}\cdot\$_{NaturalGas} \quad (9)$$

For purposes of economic analysis, geothermal energy is considered equivalent to the economic cost of natural gas (USD$/kJ).

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Results

After carrying out the four paths of the Energy Reconciliation Method to the Basic Organic Rankine Cycle, the following values expressed in Tables 2-5 were obtained, where the behavior in each case appears. In Type 1 it was observed that, if the reconciliation was fulfilled. However the order in which the method is performed is not logical, since the analysis cannot start with the Design State and then add malfunctions, since the real plants have already malfunctions. Therefore, this way of correction of malfunctions cannot be used. In Type 2 it was noted that the method did not reconcile, since it has an error of 8% in the analysis of efficiency and 2.6% in the economic analysis approximately, therefore, this path is discarded to be implemented. In Type 3 like Type 2, the road did not reach reconciliation, only that in this case it has an error of 7.84% in the analysis of efficiency and 3.17% in the economic analysis, then this path is also not suitable to be made. Finally, the procedure followed by Type 4 as well as Type 1, satisfies the Energy Reconciliation satisfactorily and also has a logical and orderly work order, since it begins with the Real State Cycle and begins to perform the corrections of the malfunctions until arriving at the State of Design.

Malfunctions		Impact on Efficiency at Constant Power			
MALF 1	ΔMalf.	Type 1	Type 2	Type 3	Type 4
1.- T_{Hin}	Δη1	-1.072	-1.072	0.8866	0.8866
2.- T_{Cin}	Δη2	0.2598	0.2452	-0.2336	-0.2214
3.- Superheat.	Δη 3	0.07576	0.05566	-0.06478	-0.04577
4.- Subcooling	Δη4	0.09087	0.08874	-0.0815	-0.07958
5. -ε_{Exp}	Δη5	-1.065	-1.151	1.066	1.152
6.- ε_{Pp}	Δη6	-0.06608	-0.08629	0.06555	0.08563
7. -ΔP_{41}	Δη7	0.00497	0.005676	-0.00497	-0.005676
8. -ΔP_{23}	Δη8	0.000208	0.0001967	-0.000208	-0.0001967
$\Delta\eta_R$-$\Delta\eta_D$	ΔηTot1	-1.772	-1.772	-1.772	-1.772
$\sum\Delta\eta_i$	ΔηTot2	-1.772	-1.914	1.633	1.772

Table 2: Comparative Analysis of Efficiency to Constant Power.

Malfunctions		Impact On Efficiency In Constant Mass Flow			
MALF 1	ΔMalf.	Type 1	Type 2	Type 3	Type 4
1.- T_{Hin}	Δη1	-1.072	-1.072	0.8866	0.8866
2.- T_{Cin}	Δη2	0.2598	0.2452	-0.2336	-0.2214
3.- Superheat.	Δη3	0.07576	0.05566	-0.06478	-0.04577
4.- Subcooling	Δη4	0.09087	0.08874	-0.0815	-0.07958
5.- ε_{Exp}	Δη5	-1.065	-1.151	1.066	1.152
6.- ε_{Pp}	Δη6	-0.06608	-0.08629	0.06555	0.08563
7.- ΔP_{41}	Δη7	0.00497	0.005676	-0.00497	-0.005676
8.- ΔP_{23}	Δη8	0.000208	0.0001967	-0.000208	-0.0001967
$\Delta\eta_R$-$\Delta\eta_D$	ΔηTot1	-1.772	-1.772	-1.772	-1.772
MALF 1	ΔηTot2	-1.772	-1.914	1.633	1.772

Table 3: Comparative Analysis of Constant Mass Flow Efficiency.

Malfunctions		Economic Impact At Constant Power			
MALF 1	ΔMalf.	Type 1	Type 2	Type 3	Type 4
1.- T_{Hin}	Δ$HR1	1.573E-04	1.573E-04	-1.530E-04	-1.530E-04
2.- T_{Cin}	Δ$HR2	-4.126E-05	-3.161E-05	4.554E-05	3.555E-05
3.- Superheat.	Δ$HR3	-1.162E-05	-7.304E-06	1.239E-05	7.555E-06
4.- Subcooling	Δ$HR4	-1.371E-05	-1.160E-05	1.562E-05	1.331E-05
5.- ε_{Exp}	Δ$HR5	1.782E-04	1.703E-04	-1.806E-04	-1.732E-04
6.- ε_{Pp}	Δ$HR6	1.246E-05	1.147E-05	-1.235E-05	-1.137E-05
7.- Δ P_{41}	Δ$HR7	-9.442E-07	-7.483E-07	9.441E-07	7.483E-07
8.- ΔP_{23}	Δ$HR8	-3.949E-08	-2.594E-08	3.949E-08	2.594E-08
$\Delta\eta_R$-$\Delta\eta_D$	Δ$HRTot1	2.804E-04	2.804E-04	2.804E-04	2.804E-04
MALF 1	Δ$HRTot2	2.804E-04	2.877E-04	-2.715E-04	-2.804E-04

Table 4: Comparative Economic Analysis to Constant Power.

An analysis of the effect of malfunctions within the Thermodynamic Cycle was also made, so in this case Type 2 was used, since it is the path that departs from the Design case and malfunctions are added separately. In this way you can see the effect of each malfunction in the cycle. Thanks to this analysis, Figures 6 and 7 were obtained in which the effect of the malfunctions in the Heat Rate and the efficiency of the cycle are observed respectively. As a conclusion, it can be presumed that the malfunctions that have the greatest effect in the Thermodynamic Cycle are the Hot Fluid Inlet Temperature (T_{Hin}) and the Expander Efficiency (ε_{Exp}).

Route of reconciliation proposal

Derived from the results and observations of the case study, we

Malfunctions		Economic Impact At Constant Mass Flow			
MALF 1	ΔMalf.	Type 1	Type 2	Type 3	Type 4
1.- T_{Hin}	Δ$HR1	1.573E-04	1.573E-04	-1.530E-04	-1.530E-04
2.- T_{Cin}	Δ$HR2	-4.126E-05	-3.161E-05	4.554E-05	3.555E-05
3.- Superheat.	Δ$HR3	-1.162E-05	-7.304E-06	1.239E-05	7.555E-06
4.- Subcooling	Δ$HR4	-1.371E-05	-1.160E-05	1.562E-05	1.331E-05
5.- ε_{Exp}	Δ$HR5	1.782E-04	1.703E-04	-1.806E-04	-1.732E-04
6.- ε_{Pp}	Δ$HR6	1.246E-05	1.147E-05	-1.235E-05	-1.137E-05
7.- ΔP_{41}	Δ$HR7	-9.442E-07	-7.483E-07	9.441E-07	7.483E-07
8.- ΔP_{23}	Δ$HR8	-3.949E-08	-2.594E-08	3.949E-08	2.594E-08
$\Delta\eta_R$-$\Delta\eta_D$	Δ$HRTot1	2.804E-04	2.804E-04	2.804E-04	2.804E-04
$\sum\Delta\eta_i$	Δ$HRTot2	2.804E-04	2.877E-04	-2.715E-04	-2.804E-04

Table 5: Economic Comparative Analysis to Constant Mass Flow.

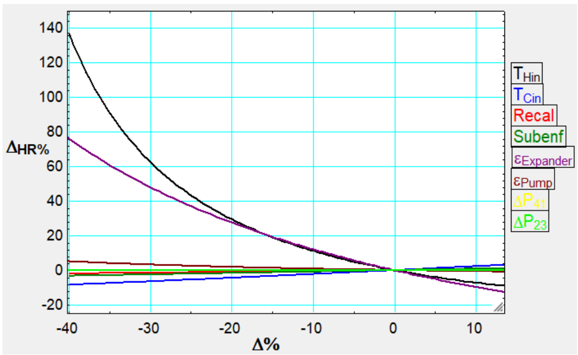

Figure 6: Behavior of the heat rate with respect to malfunctions.

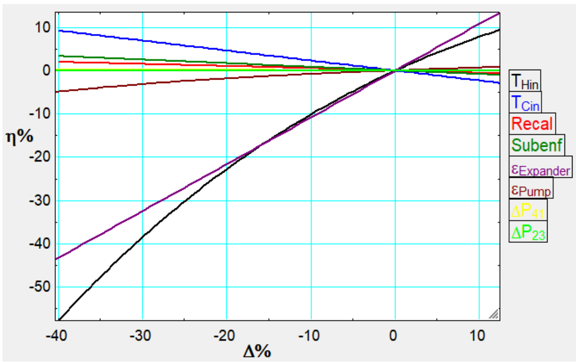

Figure 7: Efficiency behavior with respect to malfunctions.

propose for this article the type 4 methodology with its route that starts from the primary elements, which are the controls, followed by the secondary elements that are the intrinsic elements and finally the environmental ones is shown in Tables 6 and 7, in this way the best use of the reconciliation methodology with this procedure is proposed starting from the performance test status, in other words, the current status of the plant and correcting each one of the processes. The proposal arises from that has been derived by interview with real operators in real plants or heads of maintenance and engineers in process and it has to be the best route for the natural actions that are carried out in the field to correct malfunctions in a process (Figure 8).

Malfunctions			**Impact on efficiency**	
Type of Malfunction	**Input variable**	**ΔMalf.**	**Constant power**	**Constant mass flow**
Control	1. Superheat.	Δη1	-0.06478	-0.06478
	2. Subcooling	Δη2	-0.08155	-0.08155
Intrinsic	3. ε_{Exp}	Δη3	1.047	1.047
	4. ε_{Pp}	Δη4	0.063	0.063
	5. ΔP_{41}	Δη5	-0.004318	-0.004318
	6. ΔP_{23}	Δη6	-0.0001886	-0.0001886
Environmental	7. T_{Hin}	Δη7	1.058	1.058
	8. T_{Cin}	Δη8	-0.2452	-0.2452
	$\Delta\eta_R$-$\Delta\eta_D$	ΔηTot1	-1.772	-1.772
	$\sum\Delta\eta_i$	ΔηTot2	-1.772	-1.772

Table 6: Effect of malfunctions on global efficiency with constant power operation mode and constant steam mass flow.

Malfunctions			**Impact on heat rate**	
Type of Malfunction	**Input variable**	**ΔMalf.**	**Constant power**	**Constant mass flow**
Control	1. Superheat.	**Δ**$HR1	1.239E-05	1.239E-05
	2. Subcooling	**Δ**$HR2	1.586E-05	1.586E-05
Intrinsic	3. ε_{Exp}	**Δ**$HR3	-1.835E-04	-1.835E-04
	4. ε_{Pp}	**Δ**$HR4	-9.794E-06	-9.794E-06
	5. ΔP_{41}	**Δ**$HR5	6.673E-07	6.673E-07
	6. ΔP_{23}	**Δ**$HR6	2.916E-08	2.916E-08
Environmental	7. T_{Hin}	**Δ**$HR7	-1.477E-04	-1.477E-04
	8. T_{Cin}	**Δ**$HR8	3.161E-05	3.161E-05
	$\Delta\eta_R$-$\Delta\eta_D$	**Δ**$HRTot1	2.804E-04	2.804E-04
	$\sum\Delta\eta_i$	**Δ**$HRTot2	-2.804E-04	-2.804E-04

Table 7: Effect of malfunctions on Heat Rate with constant power operation mode and constant steam mass flow.

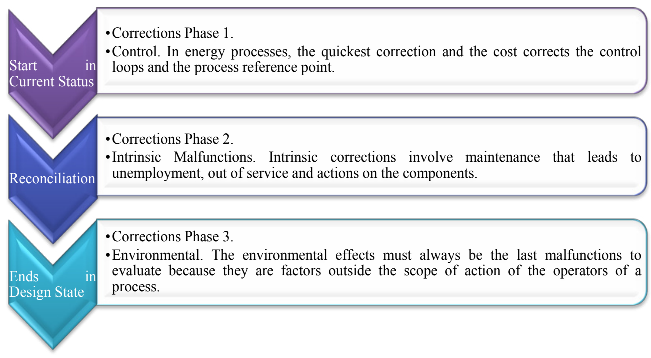

Figure 8: Philosophical framework for the correction of malfunctions, reconciling phase 1 control malfunctions, phase 2 intrinsic malfunctions and phase 3 environmental malfunctions.

Conclusions

Derived from the analysis of the results and the errors that were observed in the type 1, 2 and 3 models in this article, route 4 was proposed in its aspects discussed in the previous section, this improves the reliability of the model and allows users to have always a solution to the impact that makes any malfunction or that exerts each malfunction in the systems and gives a better tool and more precision in the magnitude of the impact, either in fuel, in Heat Rate or in some other global indicator of the reconciliation methodology by modules, in this way the scientific community is left with its opinion and can continue to be applied in any advanced energy system.

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