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FIELD MEASUREMENT RECONCILIATION FOR COMBINED CYCLE HEAT RECOVERY STEAM GENERATOR MONITORING

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ABSTRACT

Long term monitoring and diagnostic of power plants is a permanent challenge for the energy companies. In particular with the increase of flexible exercise (e.g. daily start-up and shut-down cycles, part load operations) the definition of proper diagnostic indicators becomes mandatory. Different monitoring strategies were developed, implemented and tested for the main machineries of combined cycle power plants (e.g. Gas Turbine, Heat Recovery Steam Generator, Steam Turbine, Pumps) to prevent fault or failure or to plan/evaluate the maintenance activities.

This work focuses on the first principles health assessment of the Heat Recovery Steam Generator (HRSG). At first a brief analysis about the relationship between the global HRSG efficiency and the GT net power is presented. From an initial global study the attention has been addressed to a single component analysis focusing on the section that involves the first three heat exchangers in the HRSG gas path (named SH2, RH and SH1 respectively). This choice has been done for two main reasons: firstly these heat exchangers are the most important in terms of quality of energy recovered (higher temperatures means higher exergies), secondly this section has the highest number of measurement points which allows redundancy in energy balances. This second point is the key for the implementation of an effective validation phase based on Data Reconciliation and Gross Error Detection in order to improve the accuracy of the results and show the effectiveness of such techniques in the power plant monitoring. Several input set of data have been preprocessed identifying steady-state conditions and then analyzed and compared to find the optimal subset of measurements giving the best accuracy of the results.

INTRODUCTION

Combined Cycle Power Plant (CCPP) performance analysis is an important topic for the large diffusion of this kind of systems worldwide. CCPPs, in fact, have the highest efficiency between the large size power generation systems. Nowadays the effect of electricity market in Europe leads to a flexible operation, in which CCPP components are stressed by high frequency of start up and shut down (even more than one per day). Additionally fast load ramps are often requested to support the grid stability. Such operating method has an impact on the components performance and structural integrity.

The correct evaluation of the efficiency and thus performance degradation of the whole system and its subsystem is a valuable method to drive action of condition based maintenance and in general to optimize the plant operation.

Several analyses can be conducted to monitor the HRSG functionality:

- performance analysis,
- structural / chemical analysis.

Procedure for the HRSG performance assessment was presented by Cafaro et al. [1,2] focusing on the evaluation of diagnostic indicators for real applications; the effect of the GT degradation on HRSG and cycle performance was discussed by Zwebek and Pilidis [3].

On the other hand, evaluation of material stresses during transient are mandatory in the new market scenario. Today's analytical techniques to assess transient behavior and the associated stresses and creep or fatigue damage can be used in a combination with off-line analysis and on-line monitoring to better quantify the consequences of this flexible operation, Bauver and Decoussemaker [4] presented assessment techniques, inspection methodologies and monitoring tools focused on HRSG; chemical monitoring of the HRSG and the main corrosion mechanisms are presented by Dooley [5].

Long term monitoring is a mandatory issue for companies working in the energy production market, also manufacturers exploit their deep knowledge of power plant system to create their own monitoring system basing on process data acquired from all the production units and stored in centralized dedicated servers.

Supervision strategy for HRSG transient stresses are already implemented on the DCS Power plants, with the Boiler Stress Evaluator, moreover operating procedure to reduce stresses during start-up and shut-down were put in place to face market requirements minimizing the company assets depletion. Then the main focus of this work is the performance monitoring over time. In particular, the effect of Data Reconciliation on raw data is going to be investigated as an improvement for results accuracy.

Data Reconciliation exploits the available knowledge about the process in the form of a model, with the aim of:

- filter data by outlier elimination
- make data consistent
- reduce the measurement uncertainties

The measurements errors are classified typically as:

- Random Error, zero-mean, normally distributed which are the results of simultaneous effect of several causes. The combination of this kind of errors during calculation brings the results to be normally distributed, then subject to an uncertainty.
- Non-Random Error, usually caused by large, short-term, non-random events. They can subdivide into:
  - measurement-related errors, sensors malfunctioning
  - process-related errors, such as process leak.

Gross Error, are part of the Non-Random Errors and occurs when measurement device provide consistently erroneous values, either high or low.

Data Reconciliation deals with random error; its aim is to align the measurement to their real value, fulfilling the first principle process equation, such as mass and energy balances as presented by Romagnoli et al. [6]. The presence of gross errors invalidates the statistical basis of data reconciliation procedures. The technique of DR crucially depends on the assumption that only random errors are present, To verify this hypothesis, reconciled data are compared to the raw one to verify with a statistical test that measurement adjustment are affected by just random error.

NOMENCLATURE

ATT	Attemperator
CCPP	Combined Cycle Power Plant
DR	Data Reconciliation
FHW	Feedwater
GED	Gross Error Detection
GT	Gas Turbine
HP	High Pressure
HRSG	Heat Recovery Steam Generator
IP	Intermediate Pressure
LP	Low Pressure
OTC	Outlet Temperature Corrected
RH	Reheater
SH	Superheater
SQP	Sequential Quadratic Programming

MONITORING OF THE HRSG PERFORMANCE

The heat recover capacity is function of the inlet conditions (GT exhaust mass flow rate and temperature). The ambient temperature and the GT load have the major impact on cycle performance. With the increase of flexible exercise, it is more common for combined cycle power plants to operate at part load. Thus, long term monitoring procedures must be able to consider also significant part-load operating points.

The actual turbine outlet temperature (green triangles) increases with the reduction of GT load, in order to maintain an optimized off-design efficiency and low emissions, as shown in Fig.1. The red and blue lines, which represent the expected values for the new and clean machine, respectively for exhaust mass flow rate and temperature, were extracted from the manufacturer curves. The green triangles and the blue squares represent the measured or calculated values for steady state and ISO condition (ambient temperature 15°C, pressure 1.013 bar, humidity 60%), respectively for exhaust mass flow rate and temperature.

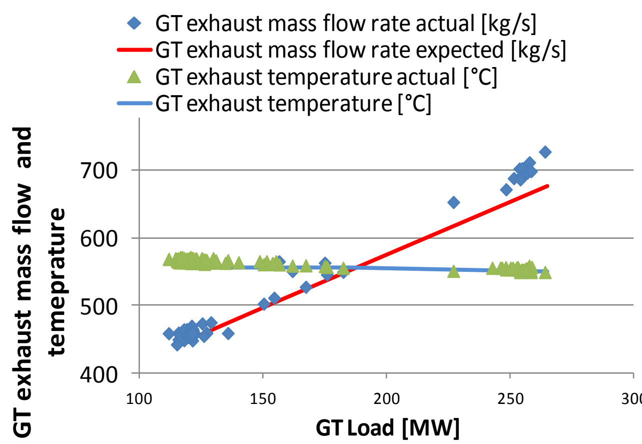

Fig.1: Expected and actual exhaust mass flow rate and temperature vs. GT load

The actual mass flow rate is calculated basing on the GT first principle balance, taking into account ambient conditions, fuel mass flow rate, air and gas compositions and discharge temperature. The outlet temperature is set by the OTC Control, so the GT degradation affects only the mass flow rate.

A lower GT efficiency results in an increase of heat released with the exhaust (Fig. 2). A higher heat load to HRSG is detrimental for its efficiency, which can be overall modeled as a counter flow heat exchanger as shown by Cafaro [1].

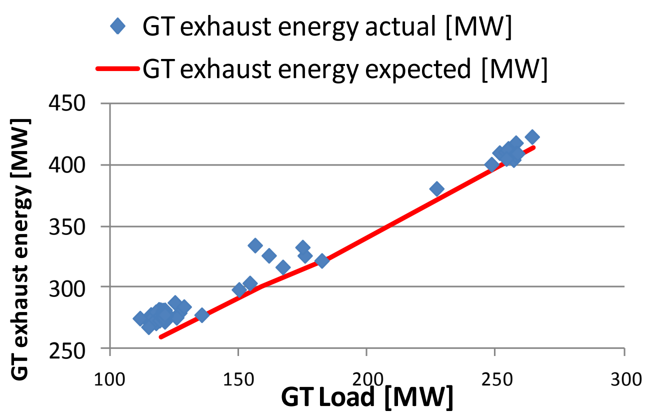

Fig. 2: Expected and actual exhaust energy vs. GT load

To monitor the energetic performance of the overall HRSG a first principle approach indicator can be defined by eq. (1) as the ratio of the steam produced by the HRSG and the energy at the GT outlet

$$\eta_{HRSG} = \frac{Q^{s}_{HRSG}}{Q^{e}_{1}} \qquad (1)$$

The GT exhaust energy is obtained through the energy balance around the GT as shown in eq. (2), taking into account the combustion chamber efficiency and the GT losses due to mechanical and electrical efficiency of the bearings and of the generator respectively. The use of the fuel Low Heating Value is justified by the discharge temperature, which does not allow condensation of the flue gas steams.

$$Q^{e}_{1} = m_{fuel} \cdot LHV \cdot \eta_{CC} + m_{air} \cdot h^{a}_{0} - P_{GT} - P_{losses} \qquad (1)$$

The HRSG steam production is evaluated as the sum of the heats of each pressure level, reheat and feedwater (Fig. 4)

$$Q^{s}_{HRSG} = Q^{s}_{HP} + Q^{s}_{IP} + Q^{s}_{LP} + Q^{s}_{RH} + Q^{w}_{FHW} \qquad (2)$$

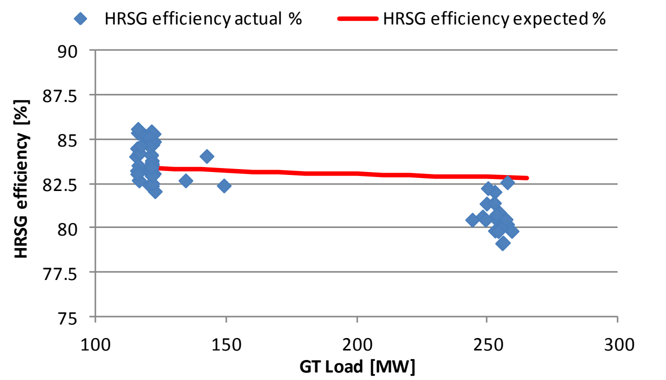

Fig. 3: Expected and actual HRSG efficiency for vs. GT load

Fig. 3 shows the HRSG efficiency behavior with respect to GT load. The expected values (red line) are derived from the CCPP heat balances solved for different ambient temperatures. The expected trend can be explained on the basis of the counter heat exchanger example: with higher ambient temperature the mass flow rate and thus the total energy entering the HRSG is reduced. This causes an increase of the specific exchange surface per unit of mass flow rate. Moreover higher ambient temperature leads to higher GT exhaust temperature and, since steam temperatures are controlled through constant values, the increase of the temperature difference increases the heat exchanged. The actual HRSG efficiency values (blue squares) follow the expected trend but are lower because of GT degradation, which causes the increase in the heat entering the boiler, with respect to the base line.

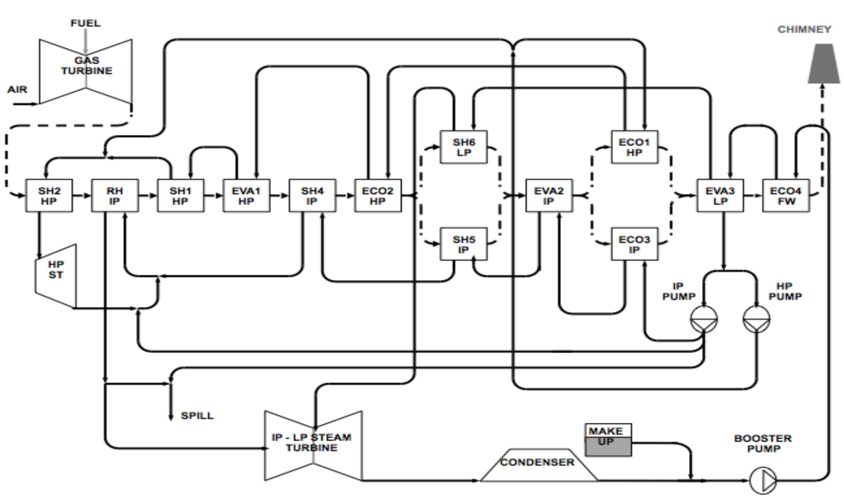

Fig. 4: HRSG scheme and mass flow measurements locations

DR CONCEPT AND FORMULATION

Globally, DR is a constrained optimization problem and various resolution methods exist in literature such as Lagrange Multipliers, successive linear DR, Sequential Quadratic Programming (SQP) and so on as presented by Romagnoli et al. [6] and Narasimhan et al. [7]. In this work a novel resolution technique based on least squares approach has been applied, having been previously validated as presented by Coco et al. [8]: it leads to a faster resolution of the minimization problem (saving about 90% of computational time compared to the other state of the art algorithm) and allows the use of the DR tool in larger set of data or with an higher number of component. Moreover the methodology can be used for a combinatorial approach in the Gross Error Identification phase (serial elimination), where resolution time of the DR loop is critical.

The general nonlinear Data Reconciliation problem can be formulated as a least squares minimization problem as follows:

$$\underset{x,u}{Min}\left(y-x\right)^{T}\Sigma^{-1}\left(y-x\right) \tag{3}$$

subject to

$$f(x,u)=0 \tag{4}$$
$$g(x,u)\le 0 \tag{5}$$

where

f : m x 1 vector of equality constraints (usually mass and energy balances);
g : q x 1 vector of inequality constraints (usually variables bounds);
Σ : n x n variance-covariance matrix;
u : p x 1 vector of unmeasured variables;
x : n x 1 vector of measured variables;
y : n x 1 vector of measured values of measurements of variables x.

INPUT DATA

The data inputs for the study have been selected at steady state; averaged value where redundant instrumentation is employed (e.g. GT outlet temperature, stack of the HRSG) was selected. The criteria used for collecting data were: stability of gas turbine and of steam pressures (controlled parameter). Five minutes time average was employed to reduce the real scattering of the field, as reported in the first three figures.

Tab. 1 lists all the variables considered in this study, specifying the tag, unit, if it is measured of not and the instrument uncertainty in case of measured variable. The uncertainties of measured variables are derived from instrument characteristics; for the gas exhaust temperatures through the heat exchangers considered in this case study (T_1, T_3, T_5 and T_6), an higher uncertainty has been considered because they are evaluated through a single instrument over a great heat exchange area (about 200 squared meters). Besides the radiant heat losses of the heat exchangers have been considered as measured variables (their values have been taken as the design values) in order to improve the redundancy of the DR problem. For this reason high uncertainties have been assumed, about 10 %.

Variables		Unit	Measured = □ Unmeasured = □	Uncertainty
Z_1	m_1	kg/s	□	1 [%]
Z_2	T_1	°C	□	5 [°C]
Z_3	m_2	kg/s	□	-
Z_4	T_2	°C	□	-
Z_5	m_7	t/h	□	-
Z_6	T_7	°C	□	-
Z_7	p_7	barg	□	-
Z_8	m_8	t/h	□	1 [%]
Z_9	T_8	°C	□	2.5 [°C]
Z_{10}	p_8	barg	□	1 [%]
Z_{11}	m_3	kg/s	□	-
Z_{12}	T_3	K	□	5 [°C]
Z_{13}	m_4	kg/s	□	-
Z_{14}	T_4	°C	□	-
Z_{15}	m_9	t/h	□	-
Z_{16}	T_9	°C	□	2.5 [°C]
Z_{17}	p_9	barg	□	1 [%]
Z_{18}	m_{10}	t/h	□	-
Z_{19}	T_{10}	°C	□	2.5 [°C]
Z_{20}	p_{10}	barg	□	1 [%]
Z_{21}	m_5	kg/s	□	-
Z_{22}	T_5	°C	□	5 [°C]
Z_{23}	m_6	kg/s	□	-
Z_{24}	T_6	°C	□	5 [°C]
Z_{25}	m_{11}	t/h	□	-
Z_{26}	T_{11}	°C	□	-
Z_{27}	p_{11}	barg	□	1 [%]
Z_{28}	m_{12}	t/h	□	-
Z_{29}	T_{12}	°C	□	-
Z_{30}	p_{12}	barg	□	-
Z_{31}	m_{13}	t/h	□	1 [%]
Z_{32}	T_{13}	°C	□	2.5 [°C]
Z_{33}	p_{13}	barg	□	1 [%]
Z_{34}	m_{14}	t/h	□	-
Z_{35}	T_{14}	°C	□	-
Z_{36}	p_{14}	barg	□	-
Z_{37}	m_{15}	t/h	□	-
Z_{38}	T_{15}	°C	□	-
Z_{39}	p_{15}	barg	□	-
Z_{40}	Q_{radSH2}	kW	□	10 [%]
Z_{41}	Q_{radRH}	kW	□	10 [%]
Z_{42}	Q_{radSH1}	kW	□	10 [%]

Tab. 1: Variables considered in the DR problem

DR PROBLEM APPLIED TO A SPECIFIC HRSG SECTION

After a global analysis on HRSG efficiency behavior vs. GT load, we focused on the first three heat exchangers (SH2, RH, SH1) of the HRSG. These heat exchangers are the most important in terms of quality of energy recovered (higher temperatures means higher exergies). For this reason, this section has several measurement points which allows redundancy in energy balances. So DR has been applied to the first three heat exchangers (SH2, RH, SH1) of the HRSG. The simplified layout is shown in Fig. 5.

In this DR problem there are 42 variables, 19 measured and 23 unmeasured, as shown in Tab. 1.

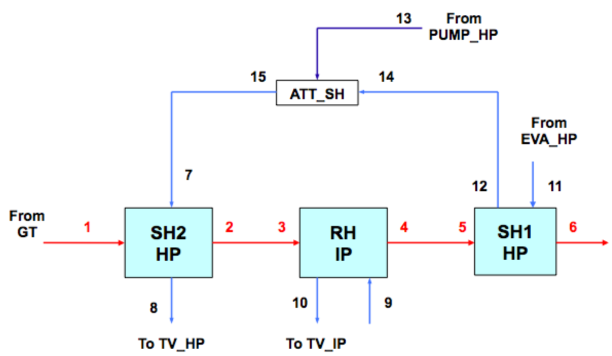

Fig. 5: Layout of the first three HRSG heat exchangers

A steady state DR based on mass and energy balances was developed. Moreover, the pressure drop equation has been considered for each heat exchanger. The saturation temperature equation in function of saturation pressure has also been considered for the steam at the first superheater (SH1_HP) inlet. Finally, all the equations related to the connection nodes have been considered (in this case study there are 4 nodes).

The total number of process equations is 26; they are listed for each component in the followings.

SH2_HP (High Pressure Superheater 2)

$$\dot{m}_1 - \dot{m}_2 = 0 \tag{6}$$

$$\dot{m}_7 - \dot{m}_8 = 0 \tag{7}$$

$$\dot{m}_1 \cdot h_1 - \dot{m}_2 \cdot h_2 + \dot{m}_7 \cdot h_7 - \dot{m}_8 \cdot h_8 - Q_{radSH2HP} = 0 \tag{8}$$

$$p_7 - p_8 - \Delta p\left(\dot{m}_7, T_7, T_8\right) = 0 \tag{9}$$

RH_IP (Intermediate Pressure Reheater)

$$\dot{m}_3 - \dot{m}_4 = 0 \tag{10}$$

$$\dot{m}_9 - \dot{m}_{10} = 0 \tag{11}$$

$$\dot{m}_3 \cdot h_3 - \dot{m}_4 \cdot h_4 + \dot{m}_9 \cdot h_9 - \dot{m}_{10} \cdot h_{10} - Q_{radRHIP} = 0 \tag{12}$$

$$p_9 - p_{10} - \Delta p\left(\dot{m}_9, T_9, T_{10}\right) = 0 \tag{13}$$

SH1_HP (High Pressure Superheater 1)

$$\dot{m}_5 - \dot{m}_6 = 0 \tag{14}$$

$$\dot{m}_{11} - \dot{m}_{12} = 0 \tag{15}$$

$$\dot{m}_5 \cdot h_5 - \dot{m}_6 \cdot h_6 + \dot{m}_{11} \cdot h_{11} - \dot{m}_{12} \cdot h_{12} - Q_{radSH1HP} = 0 \tag{16}$$

$$p_{11} - p_{12} - \Delta p\left(\dot{m}_{11}, T_{11}, T_{12}\right) = 0 \tag{17}$$

$$T_{11} - T_{sat}\left(p_{11}\right) = 0 \tag{18}$$

ATT_SH (Superheater attemperator)

$$\dot{m}_{14} + \dot{m}_{13} - \dot{m}_{15} = 0 \tag{19}$$

$$\dot{m}_{14} \cdot h_{14} + \dot{m}_{13} \cdot h_{13} - \dot{m}_{15} \cdot h_{15} = 0 \tag{20}$$

$$p_{14} - p_{15} = 0 \tag{21}$$

Node 2-3

$$\dot{m}_2 - \dot{m}_3 = 0 \tag{22}$$

$$T_2 - T_3 = 0 \tag{23}$$

Node 4-5

$$\dot{m}_4 - \dot{m}_5 = 0 \tag{24}$$

$$T_4 - T_5 = 0 \tag{25}$$

Node 15-7

$$\dot{m}_{15} - \dot{m}_7 = 0 \tag{26}$$

$$T_{15} - T_7 = 0 \tag{27}$$

$$p_{15} - p_7 = 0 \tag{28}$$

Node 12-14

$$\dot{m}_{12} - \dot{m}_{14} = 0 \tag{29}$$

$$T_{12} - T_{14} = 0 \tag{30}$$

$$p_{12} - p_{14} = 0 \tag{31}$$

As aforementioned in the previous section, the radiant heat losses of the heat exchangers have been considered as measured variables. This allows the degrees of freedom in the DR problem to be greater than zero, in particular equal to 3 being the difference between the number of equations 26 and the number of observable unmeasured variables 23.

STATISTICAL GED

The statistical component of a GED strategy simply attempts to answer the question of whether gross errors are present in the data or not. It does not provide any insight on either the number of gross errors, their types, or their locations. All detection methods, either directly or indirectly, utilize the fact that gross errors in measurements cause them to violate the model constraints. If measurements do not contain any random errors, then a violation of any of the model constraints by the measured values can be immediately interpreted as due to the presence of gross errors. This is a purely deterministic method.

The most commonly used statistical techniques for detecting gross errors are based on hypothesis testing. In a GED case, the null hypothesis H_0 is that no gross error is present, and the alternative hypothesis H_1 is that one or more gross errors are present in the system. All statistical techniques for choosing between these two hypotheses make use of a test statistic, which is a function of the measurements and constraint model. The test statistic is compared with a pre-specified threshold value and the null hypothesis is rejected or accepted, respectively, depending on whether the statistic exceeds the threshold or not. The threshold value is also known as the test criterion or the critical value of the test. The outcome of hypothesis testing is not perfect. A statistical test may declare the presence of gross errors, when in fact there is no gross error (H_0 is true). In this case, the test commits a Type I error or gives rise to a false alarm. On the other hand, the test may declare the measurements to be free of error, when in fact one or more gross errors exists (Type II error). The power of a statistical test, which is the probability of correct detection, is equal to 1-Type II error probability. The power and Type I error probability of any statistical test are intimately related. By allowing a larger Type I error probability, the power of a statistical test can be increased. Therefore, in designing a statistical test, the power of the test must be balanced against the probability of false detection. If the probability distribution of the test statistic can be obtained under the assumption of the null hypothesis, then the test criterion can be selected so that the probability of Type I error is less than or equal to a specified value α. The parameter α is also referred to as the level of significance for the statistical test.

The global test, which was the first test proposed [9,10,11], uses the test statistic given by the following equation

$$\gamma = r^T \cdot V^{-1} \cdot r \tag{11}$$

where r is the vector of balance residuals given by

$$r = J_x \cdot (y - x) \tag{12}$$

where J_x is the jacobian matrix with respect measured variables, y is the vector of measurements and x is the vector of reconciled values.

In the absence of gross errors, the vector r follows a multivariate normal distribution with zero mean value and variance-covariance matrix V given by

$$V = \mathrm{cov}(V) = J_x \cdot \Sigma \cdot J_x^T \tag{13}$$

In the presence of gross errors, the elements of residual vector r reflect the degree of violation of process constraints (material and energy conservation laws). On the other hand, matrix V contains information of the process structure (matrix J_x) and the measurement variance-covariance matrix, Σ The two quantities, r and V, can be used to construct statistical tests which can detect the existence of gross errors. Under the null hypothesis H_0, the above statistic follows a χ^2 (chi-square) distribution with ν degrees of freedom. If the test criterion is chosen as $\chi^2_{1-\alpha,\nu}$, where $\chi^2_{1-\alpha,\nu}$ is the critical value of χ^2 distribution at the chosen α level of significance, then H0 is rejected and a gross error is detected, if

$$\gamma \geq \chi^2_{1-\alpha,\nu} \tag{14}$$

This choice of the test criterion ensures that the probability of Type I error for this test is less than or equal to α. The global test combines all the constraint residuals in obtaining the test statistic, and therefore gives rise to a multivariate or collective test that embodies the process knowledge.

This statistical approach is used to filter out data that are not consistent with the equations (for this work a degree of 95% of significance was chosen).

RESULTS

Fig. 6, 7 and 8 show a comparison between the raw (red) and reconciled values (blue) of the heat exchangers efficiencies SH2_HP, RH_IP and SH1_HP, respectively. The green values are related to the efficiencies discarded after the reconciliation process, because of the high value of the test statistic γ. This indicator gives a suggestion of the correction that have to be added to the measured data set to fulfill the energy balance equation. When γ exceeds the statistical threshold chi-square, a gross error is detected and the measured data set is discarded as not reconcilable. It can be noticed that the data DR reduces the efficiency scattering as well as the final uncertainties.

Tab. 2 presents a comparison of the uncertainties of measured and reconciled variables.

Variables		Unit	Uncertainty of measured variables	Uncertainty of reconciled variables
Z_1	m_1	kg/s	1 [%]	0.97 [%]
Z_2	T_1	°C	5 [°C]	4.01 [°C]
Z_8	m_8	t/h	1 [%]	0.99 [%]
Z_9	T_8	°C	2.5 [°C]	2.49 [°C]
Z_{10}	p_8	barg	1 [%]	0.99 [%]
Z_{12}	T_3	K	5 [°C]	3.92 [°C]
Z_{16}	T_9	°C	2.5 [°C]	2.49 [°C]
Z_{17}	p_9	barg	1 [%]	0.85 [%]
Z_{19}	T_{10}	°C	2.5 [°C]	2.49 [°C]
Z_{20}	p_{10}	barg	1 [%]	0.87 [%]
Z_{22}	T_5	°C	5 [°C]	3.94 [°C]
Z_{24}	T_6	°C	5 [°C]	4.08 [°C]
Z_{27}	p_{11}	barg	1 [%]	0.97 [%]
Z_{31}	m_{13}	t/h	1 [%]	1 [%]
Z_{32}	T_{13}	°C	2.5 [°C]	2.49 [°C]
Z_{33}	p_{13}	barg	1 [%]	0.99 [%]
Z_{40}	Q_{radSH2}	kW	10 [%]	9.99 [%]
Z_{41}	Q_{radRH}	kW	10 [%]	9.99 [%]
Z_{42}	Q_{radSH1}	kW	10 [%]	9.99 [%]

Tab. 2: Comparison of the uncertainties of measured and reconciled variables

The evaluation of the efficiency uncertainties of the heat exchangers is made on the indication of the ASME 19.1 [12] on the error propagation. Tab. 3 shows the uncertainties of the heat exchanger efficiencies.

Heat Exchanger	Efficiency uncertainty using measured variables	Efficiency uncertainty using reconciled variables
SH2_HP	3.91 [%]	3.44 [%]
RH_IP	2.23 [%]	2.01 [%]
SH1_HP	5.38 [%]	3.58 [%]

Tab. 3: Comparison of the uncertainties of measured and reconciled variables

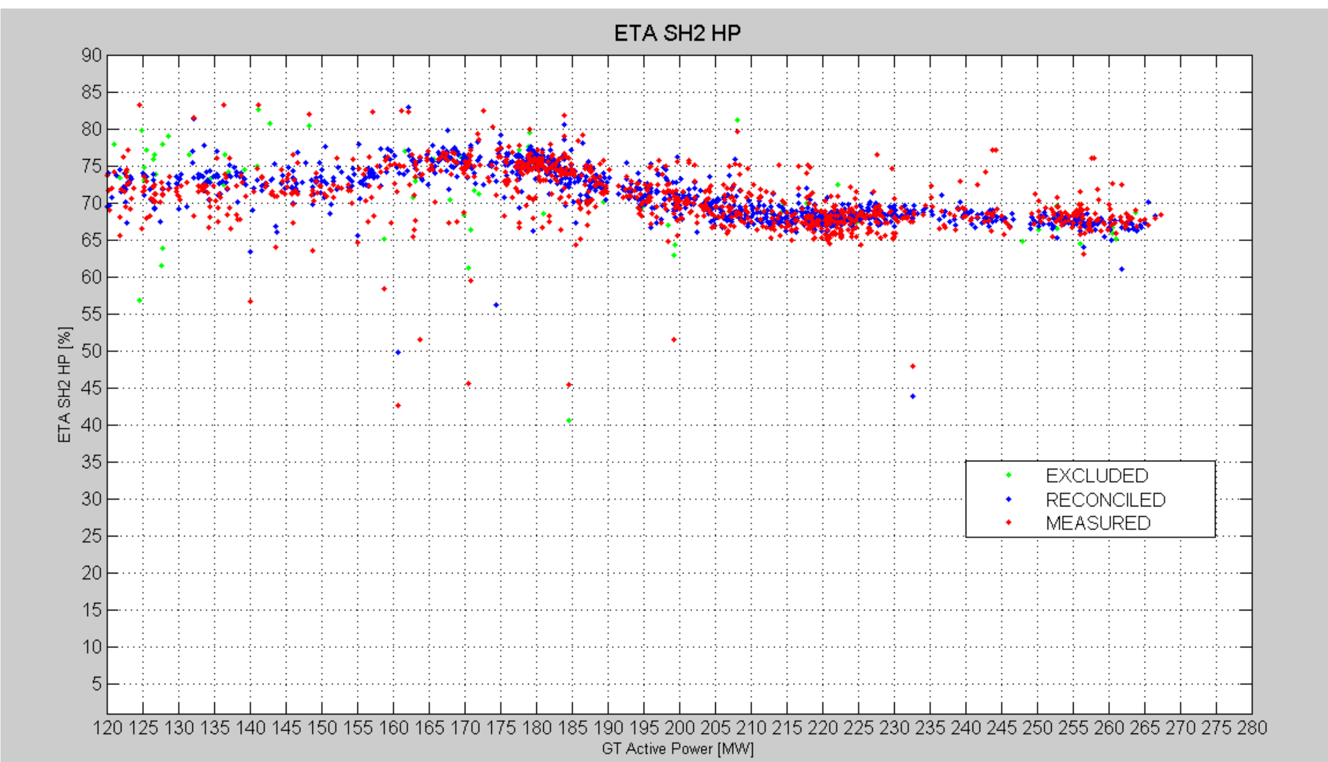

Fig. 6: comparison between raw and reconciled SH2_HP efficiencies

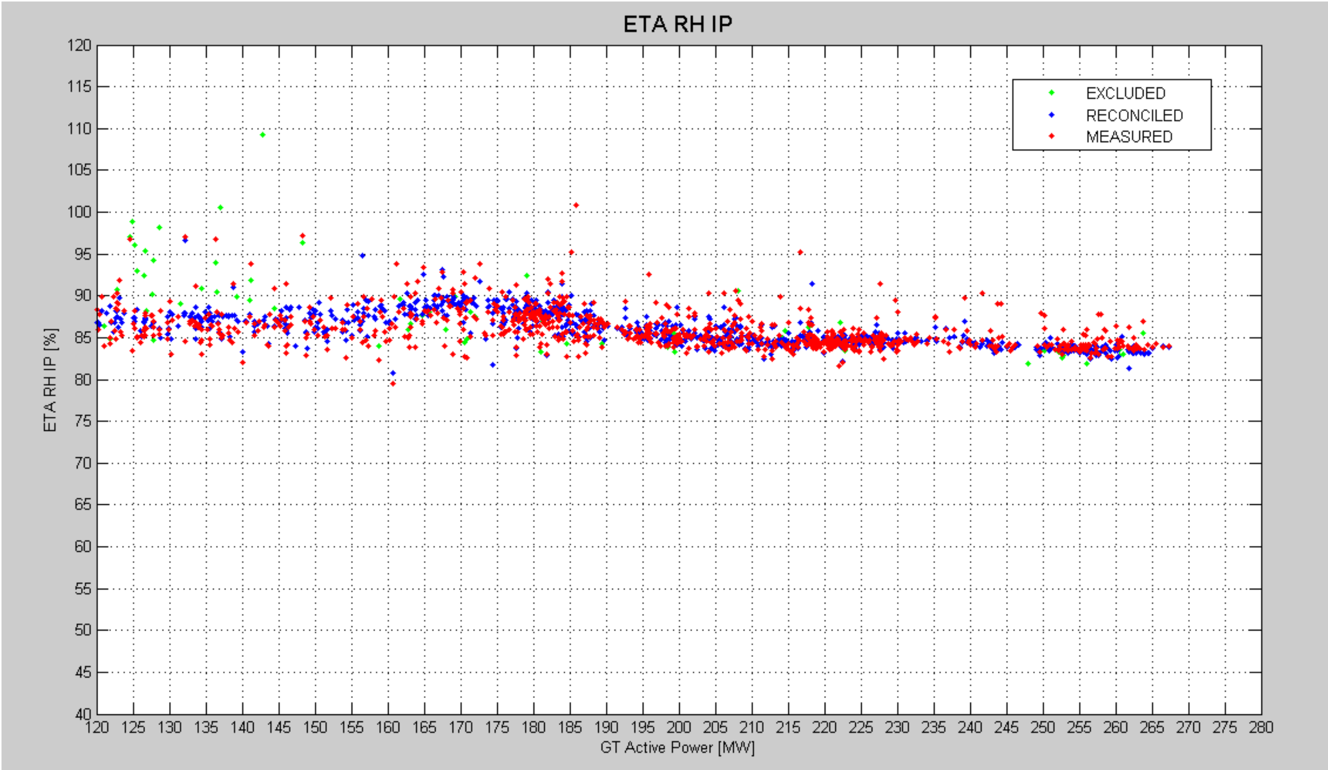

Fig. 7: comparison between raw and reconciled RH_IP efficiencies

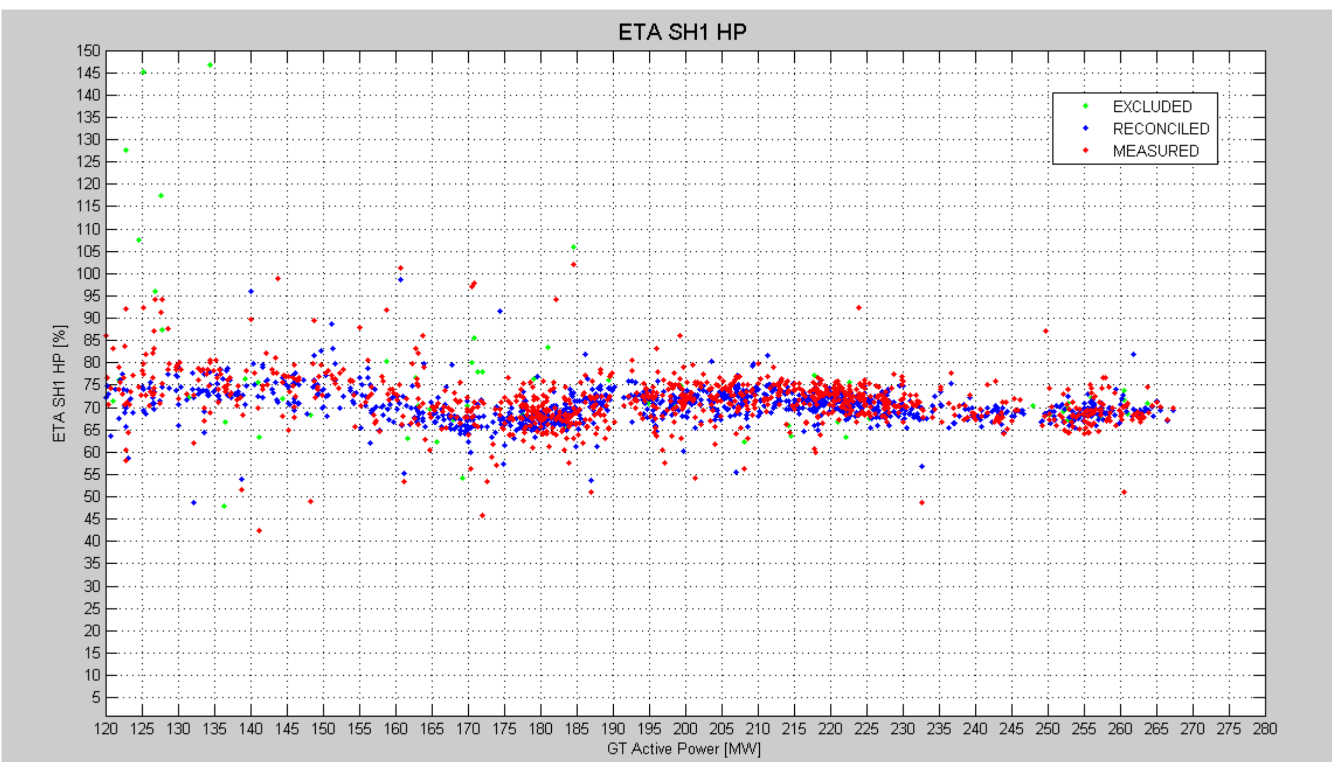

Fig. 8: comparison between raw and reconciled SH1_HP efficiencies

CONCLUSIONS

In this work the effect of data reconciliation on long term monitoring data was presented and tested. First of all, the relation between GT load and HRSG efficiency was highlighted. A Data Reconciliation problem was set implementing energy balance equation around each one of the first three heat exchangers of HRSG.

It was proven that DR is an effective instrument to:

- filter data by outlier elimination
- make data consistent
- reduce the measurement uncertainties

The effects of these enhancements were shown on the target indicators: the heat exchanger efficiencies SH2_HP, RH_IP and SH1_HP respectively.

These efficiencies are characterized by the same decreasing trend of the global HRSG efficiency indicator with respect to GT load.

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