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DIAGNOSIS OF GAS TURBINE OPERATING STATE IN NATURAL GAS COMPRESSION PLANTS

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ABSTRACT

In this paper, a methodology for gas turbine health determination based on a Gas Path Analysis method and a technique for sensor faults detection and isolation, used to increase the diagnostic analysis reliability, are presented.

The methodology for gas turbine operating state determination has been applied to gas turbines working in the ENI–Divisione Agip natural gas compression station of Casalborsetti (Ravenna - Italy) and the first results are presented.

NOMENCLATURE

E	error
M	mass flow rate
N	rotational speed
NGV	variable nozzle angular position
p	pressure
P	power
LHV	Lower Heating Value
R	residuals vector
RH	relative humidity
T	temperature
u	$= (u_1, \ldots, u_m)$ system input vector
X	characteristic parameters
y	$= (y_1, \ldots, y_n)$ measured system output vector
$\hat{\mathbf{y}}$	$= (\hat{y}_1, \ldots, \hat{y}_n)$ calculated system output vector
δ	threshold
σ	variance

Subscripts

amb	ambient
c	centrifugal compressor
f	fuel
*	normalized value with respect to reference value

Acronyms

C	compressor
CC	combustion chamber
F	filter
GGT	gas generator turbine
PT	power turbine

INTRODUCTION

Gas turbine maintenance can be mainly performed in the following three ways:

- "emergency" maintenance, which is carried out when the fault has already appeared;
- "scheduled" maintenance, which is widespread in industrial applications;
- "on condition" maintenance, which has been mainly applied to aircraft engines.

The "emergency" maintenance has to be avoided because of its high costs due to the damages suffered by the engine and the loss of profits due to the standstill of the production related to gas turbine stops. The "scheduled" maintenance is performed according to *a priori* schedules, regardless of the effective gas turbine health state. This strategy has the advantage that "emergency" maintenance is reduced, but this often leads to replace healthy components and to gas turbine maintenance stops longer than effectively necessary. It seems that the most suitable solution to maximize the machine availability and reduce costs is to replace or support the regular maintenance schedules with degradation demand maintenance (on condition maintenance).

In the case of the gas turbines used in the natural gas compression plants of ENI-Div. AGIP, the percentage amount of maintenance action can be divided as follows (Sebastianelli and Bosco, 1999):

1. 66% "scheduled" maintenance,
2. 34% "emergency" maintenance, whose 6% is due to gas turbine blocks.

The aim of the "on condition" maintenance is to reduce the "emergency" maintenance as much as possible and to optimize the "scheduled" maintenance, which is based on the manufacturer experience in terms of components life and performance degradation. The "on condition" maintenance may replace the scheduled maintenance actions, which do not take into account the actual gas turbine health state, with "ad hoc" actions, which instead is based on the real operating state of the machine. Therefore, the "on condition" maintenance requires the up-to-date knowledge of the actual values of the parameters, which are indices of the gas turbine components (compressor, turbines, combustion chamber) health, as efficiencies, characteristic flow passage areas and pressure drops along the gas path. This allows to plan in advance maintenance stops depending on the actual gas turbine health state, on the availability of stand-by machines and on the production requirements. Furthermore, if the actual characteristic parameters are known, it is possible to adapt the gas turbine control logic to the machine actual health state, so that it might be possible to recover up to 50% of the efficiency loss due to aging and deterioration.

This paper describes a methodology for the analysis of gas turbines health state based on Gas Path Analysis, and the techniques for the improvement of the diagnostic tool reliability. The first results of the application of the methodology for the operating state determination of gas turbines operating in the natural gas compression plant of ENI – Div. AGIP in Casalborsetti (RA - Italy) are presented.

A TECHNIQUE FOR GAS TURBINE OPERATING STATE DETERMINATION

Gas turbine operating state determination can be performed using Gas Path Analysis techniques, which, starting from measurements taken on the machine, allow the calculation of the characteristic parameters that are indices of the machine health state (Urban, 1972; Stamatis et al., 1990; Benvenuti et al., 1993, 1994; Doel, 1994a, 1994b; Bettocchi and Spina, 1999a; Bettocchi et al., 2000). In this paper, a Gas Path Analysis method developed by Bettocchi and Spina (1999a) has been used. This method determines the machine actual operating state by adapting the characteristic parameters of the gas turbine, used as inputs by a cycle program, until the real measurements taken on the machine are reproduced.

The cycle program used in the calculations must reproduce accurately the measurements taken on the machine in "new and clean" conditions. Two situations can occur:

- the Cycle Deck developed by the manufacturer is available. This cycle program reproduces the characteristic data values of a gas turbine-type, which presents *average* characteristics among gas turbine units of the same model. For this reason, the program has to be calibrated in order to represent a *particular* machine. This can be done making use of measurements referred to a chosen baseline condition (for instance, the measurements taken during an acceptance test);
- a generalized cycle program is used. In this case, first the program has to be set up, for instance by using the performance curves supplied by the manufacturer to the user, to reproduce the machine type taken into account. Then, the program can be calibrated to represent the particular machine under investigation.

In Figure 1, the procedure for the operating state determination in presented. Three different phases can be recognized:

1. in phase I, the actual values of characteristic parameters, which are indices of the gas turbine operating state, are estimated starting from the measurements taken on the machine. The cycle program estimates, with the actual boundary conditions and working point, the measurable parameters using the reference value of the characteristic parameters. Then, the calculated values are compared with the measurements taken on the machine. If the shift between these two values is greater than a fixed threshold, an iterative process is started in which an algorithm, based on a constrained minimization method, modifies the characteristic parameters and repeatedly calls the cycle program until the shifts are lowered under the threshold value.

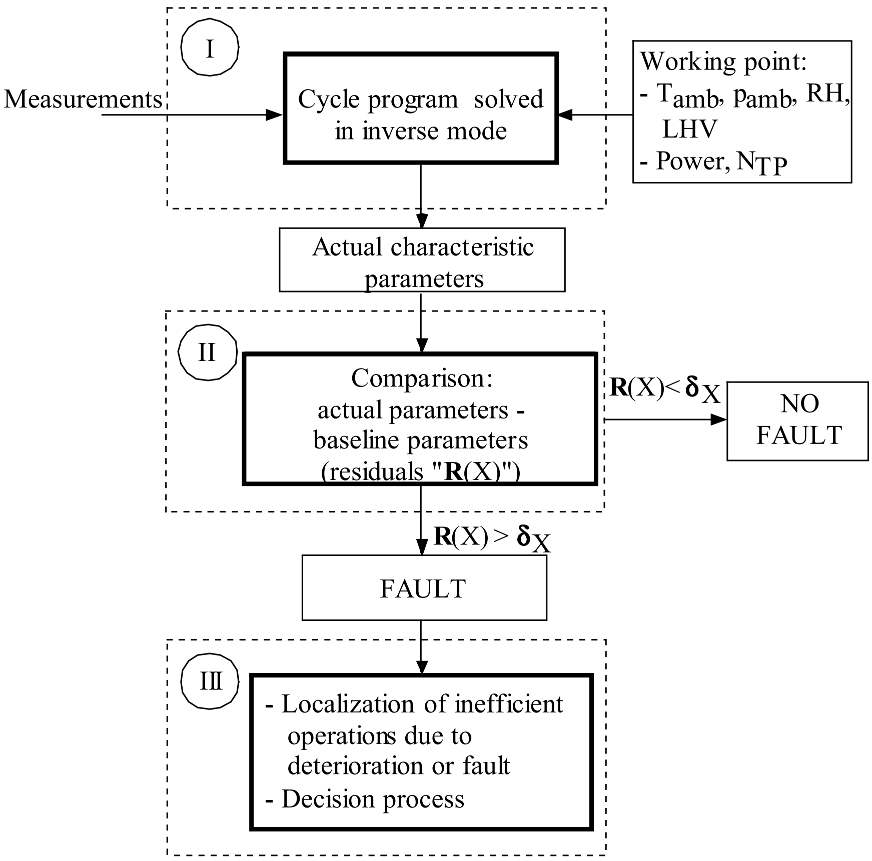

Figure 1 – Operating state determination procedure.

2. In phase II, the characteristic parameters computed in the previous step are compared with the ones chosen as baseline. So, it is possible to estimate the shift between the actual working condition and the expected one.
3. In phase III, the localization of inefficient operations due to deterioration and faults is performed and the decisional process is started. This regard:
   - the planning of the machine stop for a maintenance;
   - the possibility of on-line actions, such as compressor washing;
   - the adaptation of the gas turbine control logic to the actual working state;
   - in the worst case, the immediate stop of the machine.

One of the main problems of the techniques that make use of field measurements is the reliability of measurements themselves. In fact, the sensors used to perform these measurements are obviously affected by uncertainties that in turn can affect the characteristic parameters determination and thus the accuracy of the diagnostic analysis (Stamatis et al., 1992; Pinelli and Spina, 2000).

For these reasons, it is advisable to monitor the functionality of the sensors. This control can be performed through numerical techniques (analytical redundancy) that can support or even substitute the so-called physical redundancy (more than one sensor for each measurement) (Frank, 1990; Gertler, 1991; Isermann, 1984, 1993, 1997; Patton and Chen, 1997; Patton et al., 1989; Willsky, 1976; Young, 1981).

The analytical redundancy techniques make use of model-based approaches to calculate the estimates of measurable parameters. The fault detection is performed analyzing the residuals obtained comparing calculated and measured values of each parameter. There are various kinds of analytical redundancy techniques for the generation of the residuals, such as parity equations (Bettocchi and Spina, 1999b), dynamic observers (Simani et al., 1998) and Kalman filters (Simani and Spina, 1998). Using these techniques, it is possible to determine whether a set of measurements is reliable and cycle program can process them.

In addition, by using other techniques such as fault matrices with a canonical structure (Bettocchi et al., 1998), it is possible to isolate the faulty sensor (Fault Isolation). In this way, the non-working sensor can be repaired and substituted or, in any case, it is possible to exclude from the calculations the measurements taken with the faulty sensor.

Black box models are generally used to estimate the measurable parameters. The internal parameters are determined through identification techniques starting from measured time series of input and output data.

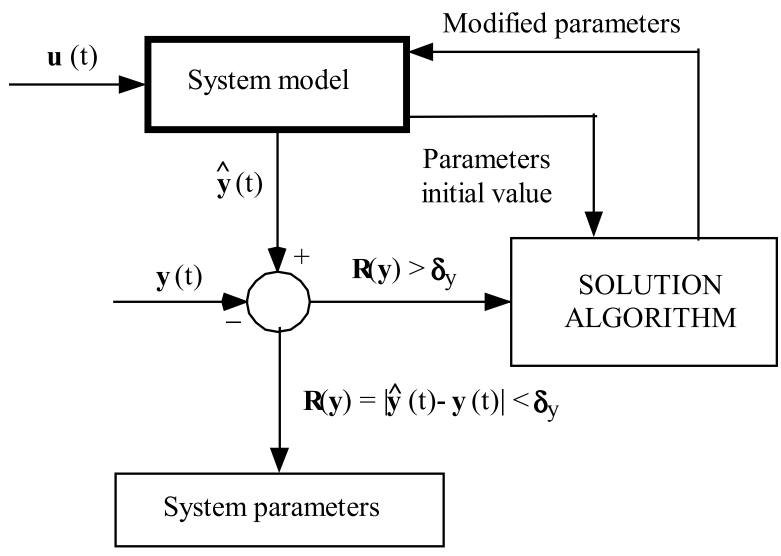

Figure 2 – Model identification for Fault Detection and Isolation

In Figure 2 the logic scheme of the identification process is reported. As can be seen, Multi Input Single Output (MISO) models have been used. These models calculate an estimate of the measurable parameters starting from other measured parameters **u**(t). In order to detect and isolate sensor faults, a number of MISO models equal to the measured parameters have been used. The way in which the models describe the real system depends on the actual state of the machine. Thus, the identification has to be periodically performed, so that false alarms due to model inaccuracies can be avoided.

The Gas Path Analysis technique used for the determination of the gas turbine characteristic parameters can give significant information on the health state of the machine, but can be affected by various sources of uncertainties. For this reason, it is advisable to support these techniques with the analysis of the machine history (Trend Analysis). The TA allows the detection of measurements variations and, through a comparison with the previous history, the determination of the probable causes of the malfunctioning.

To obtain readable information on measurement trends, the data have to be homogenized with respect of boundary conditions and working point. This can be mainly done in two ways:

1. normalizing the actual measurements with the expected ones for the same boundary conditions and working point, the latter calculated with the cycle program previously set up;
2. relating each measurement to the same reference condition, such as the design point in ISO conditions.

In this paper, the methodology described in the first point has been used, since it is available a generalized cycle program calibrated on the considered gas turbine.

The Trend Analysis needs the building of a historical database, in which the measurements taken on the machine have to be related to the maintenance actions carried out during the machine working life. The analysis of these data allows the identification of the most suitable condition to be used as reference point for the cycle program and can represent the starting point for the development of artificial intelligence techniques and of decisional algorithms.

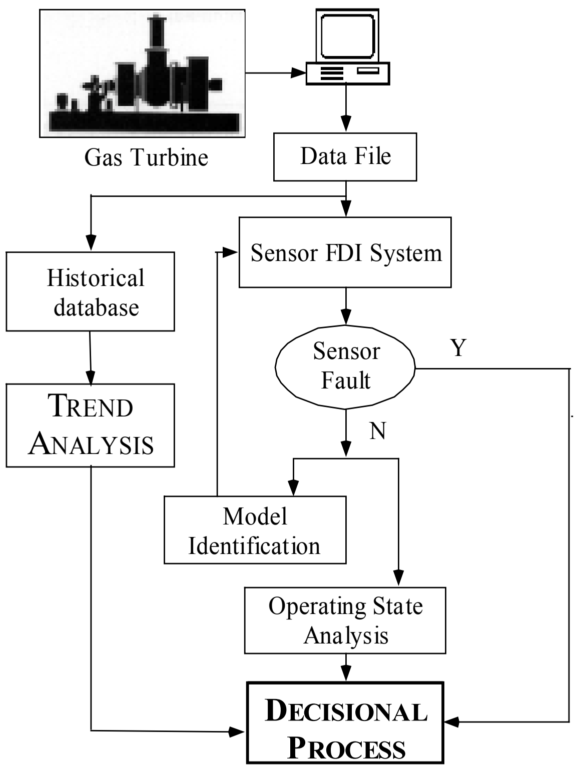

Figure 3 - Overall gas turbine diagnosis process

In Figure 3 the whole diagnosis process proposed is shown. Five steps can be recognized:

- acquisition and storage of the raw measurements on the PC of the gas turbine control system;
- generation of the data file and selection of the series of data to be processed;
- data processing by the FDI system to detect and isolate sensor faults;
- if there are no sensor faults, the data are used to identify the model and to perform the gas turbine operating state determination; if instead a sensor fault is detected and isolated, the faulty sensor must be repaired or excluded from the gas turbine diagnosis process, to avoid an incorrect evaluation of the machine health state.

SOME RESULTS OF THE DIAGNOSIS TECHINIQUE FIELD APPLICATION

The ENI-Divisione AGIP station for natural gas compression of Casalborsetti (RA) is used to raise the pressure of the gas coming from the Adriatic Sea platforms to the value requested by the SNAM gas network. This task is performed by three Nuovo Pignone ad two SOLAR gas turbines. The analysis described above as been applied to two of the Nuovo Pignone gas turbines. The design characteristics of these machines are reported in Table 1, while in Figure 4 a schematic lay out is presented. The gas turbines considered are used as centrifugal compressor drive. These centrifugal compressors raise the gas pressure from 30 bar (platform value) to 60 bar (SNAM gas network value).

As can be seen from Table 2, the fuel mass flow rate measurement is not available. In fact, the only measurement actually available is the total fuel mass flow feeding both the PGT5R/2 gas turbines and it is not possible to know them separately.

Table 1 – Characteristic of the PGT5R/2 gas turbine in ISO conditions

Power	5180 kW
Efficiency	34.7 %
Inlet air mass flow rate	25.7 kg/s
Compression ratio	9.13
Power turbine outlet temperature	543 °C
Power turbine rotational speed	10290 rpm
Gas generator rotational speed	11140 rpm

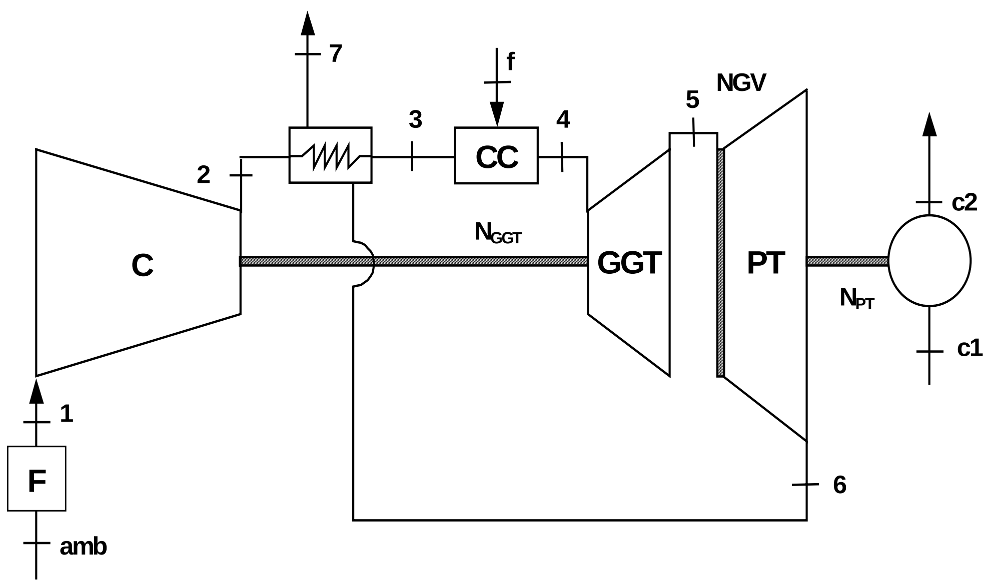

Figure 4 – Lay out of the two-shafts regenerative cycle gas turbine PGT5R/2

Table 2 – Measurements available on the machine

Turbogas:	**Centrifugal compressor:**
N_{GGT}: gas generator rotational speed	p_{c1}: gas inlet pressure
N_{PT}: power turbine rotational speed	p_{c2}: gas outlet pressure
T_1: temperature at the axial compressor inlet	T_{c1}: gas inlet temperature
T_2: temperature at the axial compressor outlet	T_{c2}: gas outlet temperature
T_3: temperature at the recuperator outlet (air side)	M_{c1}: gas mass flow rate
T_6: temperature at the power turbine outlet	
T_7: temperature at the recuperator outlet (gas side)	
p_2: pressure at the compressor outlet	
NGV: variable nozzle angular position	
T_f: temperature of the fuel gas	
p_f: pressure of the fuel gas	
Δp_{amb-1}: pressure drop of the inlet filter	

Other measurements not available but very important for a reliable diagnosis analysis are: the pressure and temperature between the gas generator and the power turbines (p_5, T_5), the gas side and air side pressure drops of the recuperator (Δp_{2-3}, Δp_{6-7}) and the air inlet mass flow rate (M_1). Standing the great importance of these measurements, the possibility of installing the relative sensors has been evaluated by the authors together with the Nuovo Pignone staff. These discussions led to the following considerations:

- the pressure and temperature between the gas generator and the power turbines are not performable;
- the air inlet mass flow rate could be implemented by measuring a pressure drop in the inlet duct of the machine, after calibration;
- the gas side and air side pressure drops of the recuperator and the fuel mass flow rate measurement for each gas turbine are supposed to be installed before the end of the current year.

In the meanwhile, the methodology for gas turbine operating state determination has began to be applied. The first step has been the set up of a generalized cycle program developed by the authors to adapt it to the PGT5R/2 gas turbines type. Then, the program has been calibrated on the particular machine through some data taken from the manufacturer Cycle Deck and supplied by the Nuovo Pignone staff. These data are representative of the machine type average characteristic and are not subjected to measurement errors.

The set up process uses generalized non-dimensional compressor and turbines maps. Solving in inverse mode the cycle program, it is possible to adapt these maps until the manufacturer data are reproduced with the best accuracy. The accuracy is judged to be satisfactory when the reconstruction error is minimal on the highest number of working point, verifying the accuracy through a comparison between the manufacturer data and the data estimated with the cycle program direct calculation.

In Figure 5, 6 and 7 the results of the set up process are reported. The Figures report the reconstruction percentage error on the calculated measurements with respect to the manufacturer ones versus the machine load and refer to three different ambient temperature values (5, 15 e 25°C). The measurements reported and taken as significant to judge the accuracy of the calculation are the fuel mass flow rate, the power turbine outlet temperature, the compressor outlet pressure and temperature and the air inlet mass flow rate.

As can be seen, the set up program estimates the manufacturer data with a maximum error generally lower than 1%. It can be also noticed as, in the case of 15 and 25 °C ambient temperature, the estimation error is minimum at the higher values of the machine load, while in the case of 5 °C ambient temperature, the variance σ is almost constant and has a value included between the minimum and the maximum values of the variances of the other two cases.

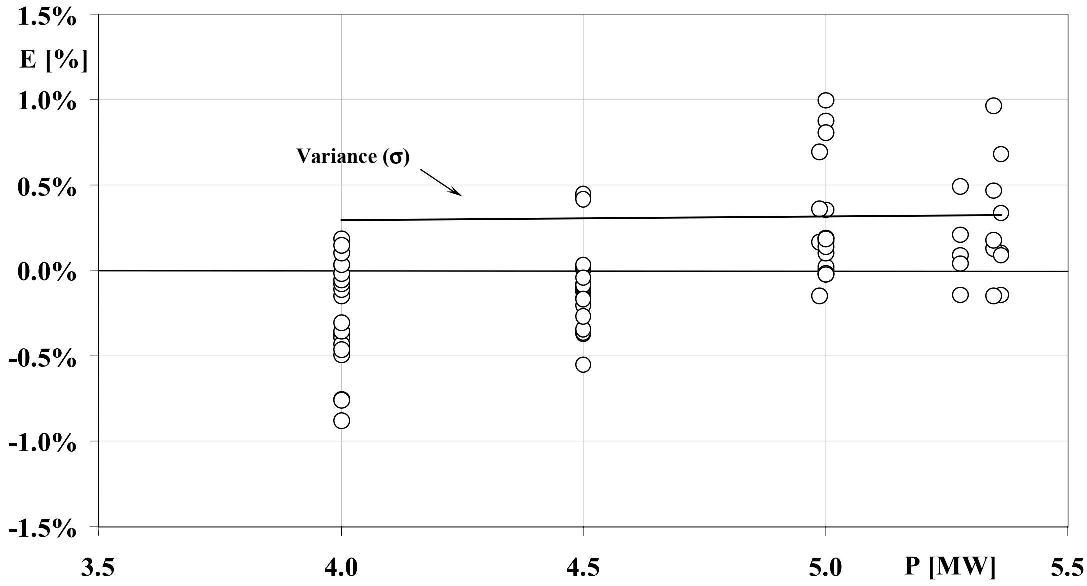

Figure 5 – Estimation error (T_{amb}=5°C)

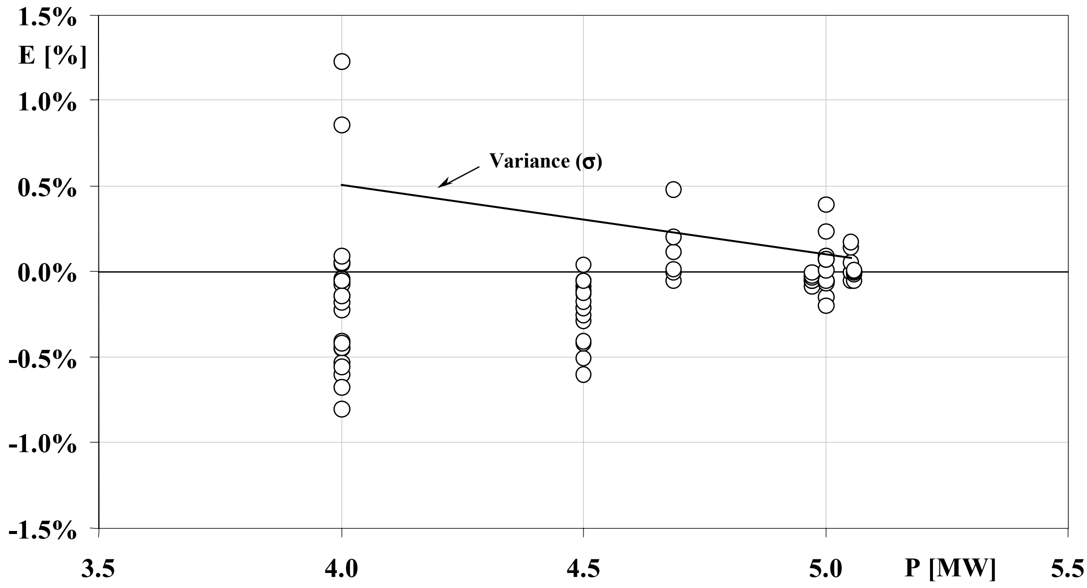

Figure 6 – Estimation error (T_{amb}=15°C)

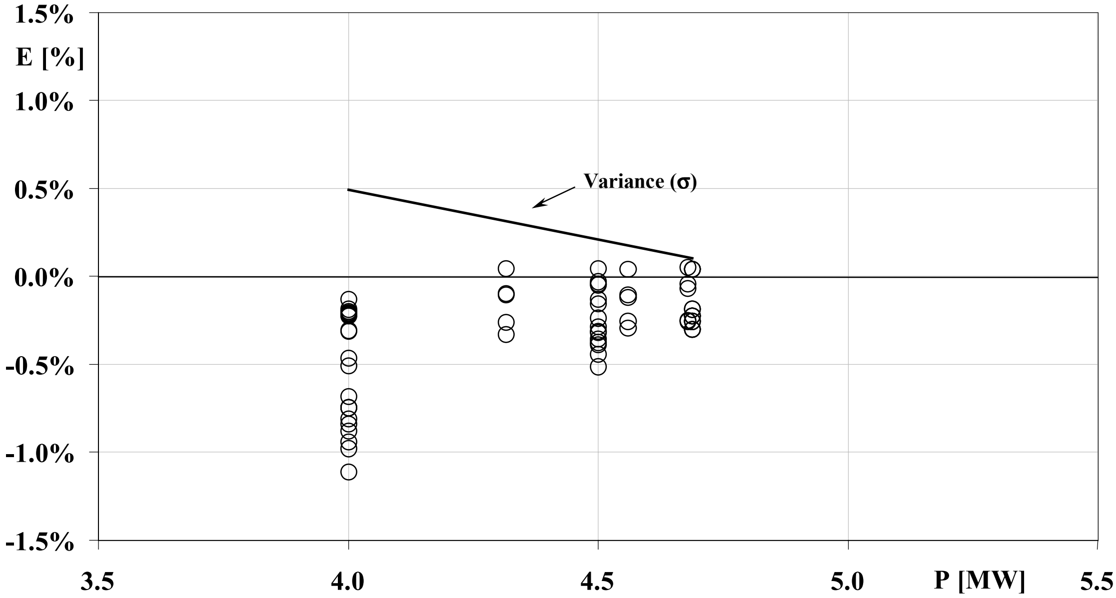

Figure 7 - Estimation error (T_{amb}=25°C)

Once the set up process has been finished, a first analysis using historical data taken during the last two years on the two PGT5R/2 under investigation was carried out, in order to evaluate if it was possible to recognize the presence of faults or deterioration of the machine components through the measurements trends. To perform this, the data has been processed to eliminate the boundary conditions and the working point influences, normalizing the actual measurements with the expected ones for the same boundary conditions and working point, the latter calculated with the cycle program previously set up. In Figure 8, the normalized trends of the pressure and temperature at the compressor outlet related to one of the two PGT5R/2 are reported. The trends are referred to a time interval in which an off-line compressor wash has been performed (March '98). As can be seen, after the compressor wash the compression ratio raised to a higher value while the compressor outlet temperature remained almost constant. This fact highlights that the compressor polytropic efficiency was increased from a value of about 86% to a value of about 87%. Moreover, since for constant turbine inlet temperature the compression ratio is a linear function of the inlet air mass flow rate, the compression ratio increase put into lights an increase of the inlet air mass flow rate. In Figure 9, the same data without normalization are reported. It can be noticed how the raw measurements trend analysis do not lead to any of the above reported considerations about the maintenance action consequence and about the compressor actual state.

The same analysis has been performed on a series of data taken at some part load working points on the second PGT5R/2 gas turbine. The data were taken before and after an off-line compressor wash on January 2000. In Figure 10, the normalized temperature and pressure at the compressor outlet are reported as a function of the machine load. As can be seen, after the maintenance the measurements taken into consideration were not remarkably varied, emphasizing that the compressor wash was probably not necessary. This fact highlights that a maintenance action based on a programmed calendar could be redundant, and that the determination of the machine actual health state could have avoided non-necessary actions.

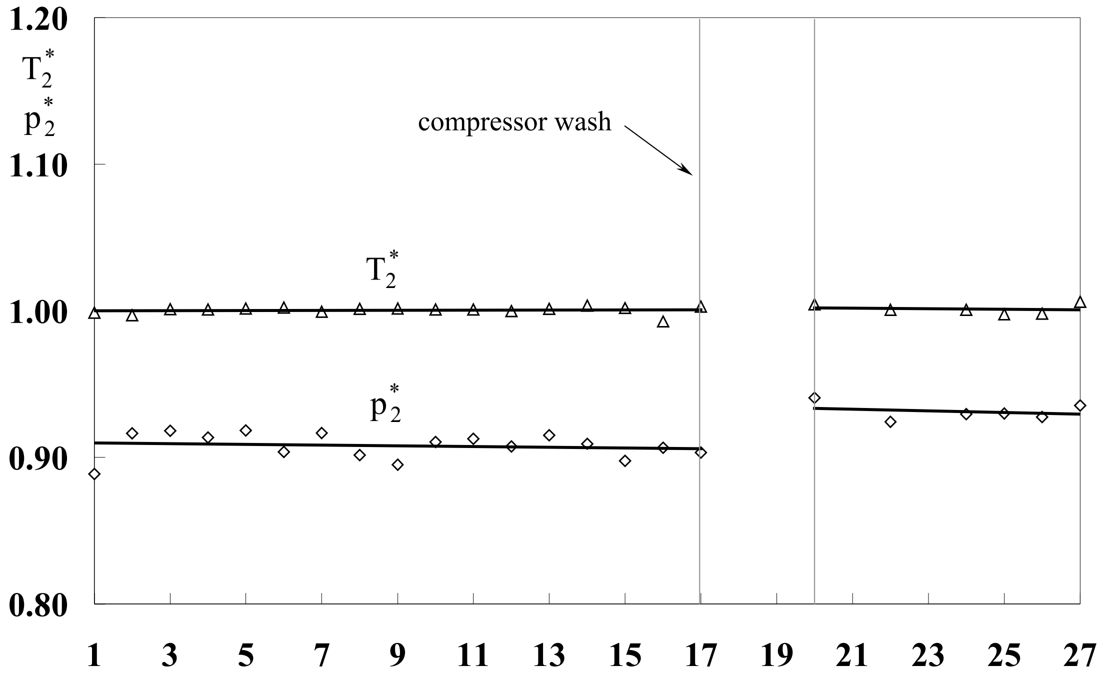

Figure 8 – Normalized pressure and temperature at the compressor outlet before and after an off-line compressor wash (March '98)

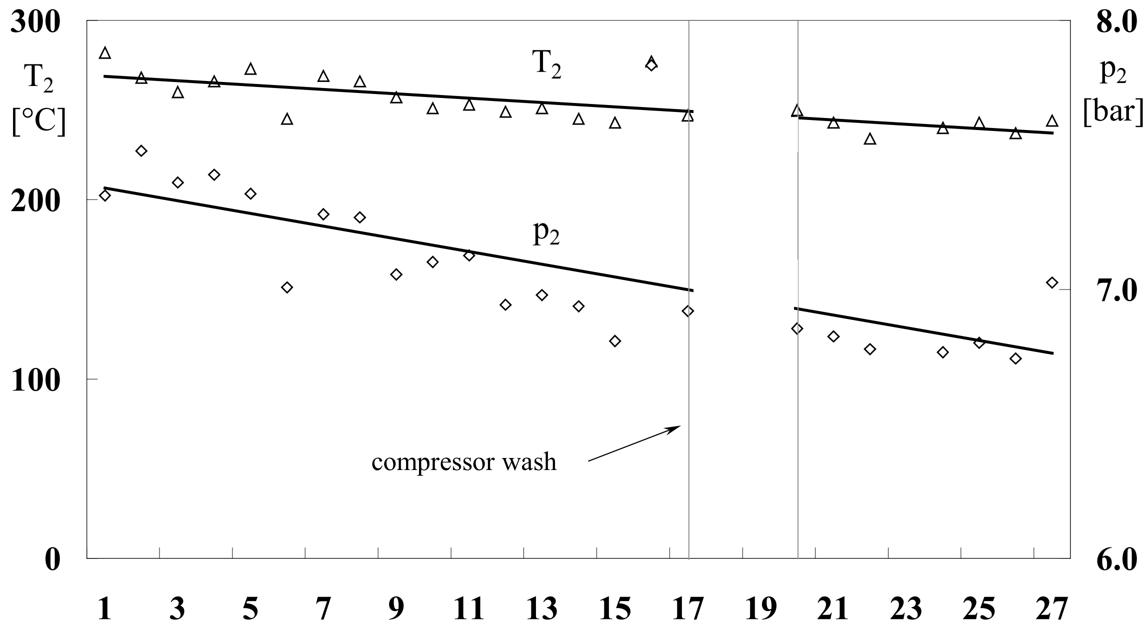

Figure 9 – Pressure and temperature at the compressor outlet before and after an off-line compressor wash (March '98)

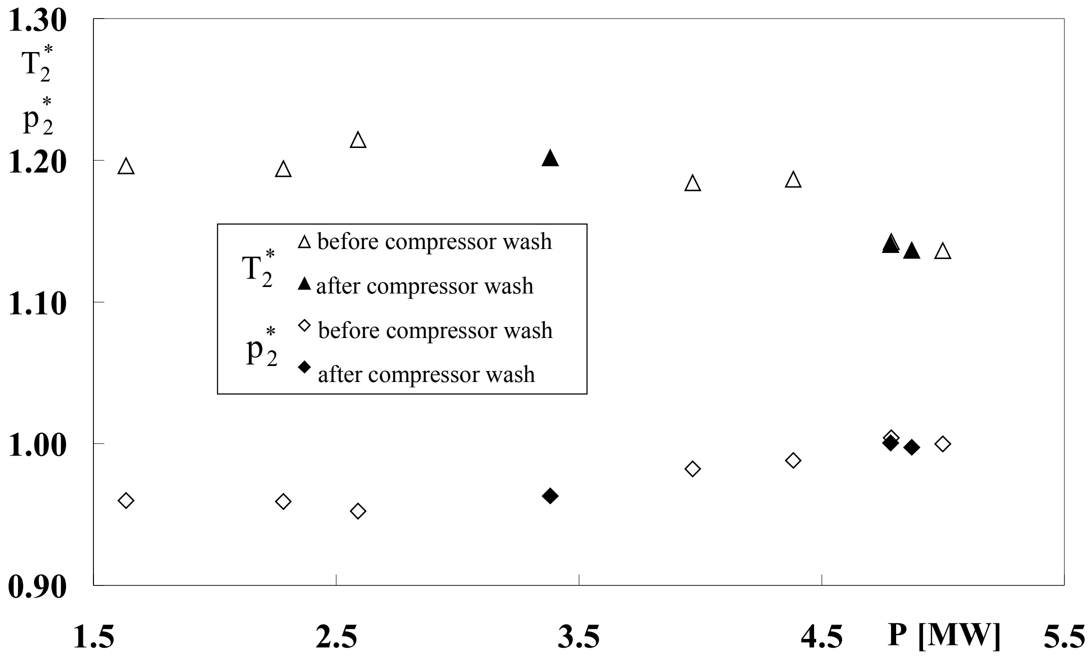

Figure 10 – Normalized pressure and temperature at the compressor outlet before and after an off-line compressor wash (January 2000)

CONCLUSIONS

In this paper, a methodology for gas turbine operating state determination and the techniques to be used to improve the reliability of the diagnostic analysis have been presented.

The main features of the diagnosis process presented are:

- a methodology for gas turbine health determination based on a Gas Path Analysis technique;
- the techniques for sensor Fault Detection and Isolation to be used to check the reliability of the measurements before they are processed by the diagnostic programs;
- a Trend Analysis method to support the diagnostic analysis.

Some preliminary results of the application of the above-mentioned methodology to a gas turbine working in an ENI - Divisione AGIP natural gas compression station have been presented. In particular, a generalised cycle program has been set up for the gas turbines taken into consideration and the Trend Analysis method proposed has been applied to some time series of field measurements. The results provided useful information and highlighted the capacity of the proposed methodology.

Future work will consider the other aspects of the methodology outlined, namely the application of the gas turbine operation state determination and the application of the sensor Fault Detection and Isolation techniques.

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