Preprints of the 10th IFAC International Symposium on Dynamics and Control of Process Systems
The International Federation of Automatic Control
December 18-20, 2013. Mumbai, India

Advanced Diagnosis of Control Loops: Experimentation on Pilot Plant and Validation on Industrial Scale

R. Bacci di Capaci*, C. Scali*, D. Pestonesi, E. Bartaloni*****

** Chemical Process Control Laboratory (CPCLab), Department of Civil and Industrial Engineering (DICI), University of Pisa, Via Diotisalvi n. 2, 56126, Pisa (Italy), e-mail: scali@ing.unipi.it*
*** ENEL, Ingegneria e Innovazione, Area Tecnica Ricerca; Via A. Pisano, n.120, 56122, Pisa (Italy),*
**** CLUI-EXERA, Via S. Orlando, n. 5, 57123, Livorno (Italy)*

Abstract: The paper presents main features of a performance monitoring system, which, in addition to variables normally registered in industrial plants (controller output OP, controlled variable PV and set-point SP), makes use of additional variables made available by intelligent instrumentations and field bus communication systems. Experimental runs on a pilot plant scale have been carried out in order to introduce different types of valve malfunctions and to define suitable indices (KPI) able to diagnose them. Subsequently, threshold values for the indices have been calibrated and a logic has been developed to assign different performance grades. It is shown how the Travel Deviation allows specific evaluation of valve status and to detect different causes of malfunctioning. The same logic is implemented in an advanced release of an existing performance monitoring system and advantages in the accuracy of diagnosis are shown. Finally the system has been successfully validated by online implementation for control loops assessment of an industrial power plant.

Keywords: Process Control Applications, Performance Monitoring, Advanced Valve Diagnostic, Stiction Detection

1. INTRODUCTION

Control loop diagnostics is widely recognised as an important aspect to face in order to improve plant efficiency and then competitiveness; in recent years quite a significant research effort has been devoted to this topics. Usually, control loops assessment and diagnosis is performed by means of the 3 variables which are more commonly acquired in industrial plants, that is: Set Point (SP), Controlled Variable (PV) and Controller Output (OP). The objective is to have a prompt diagnosis of the onset of low performance condition and to be able to distinguish among different causes. Main distinction is among external perturbations, controller tuning and valve problems: for this reason techniques able to characterize different sources have been proposed.

The significance of loop oscillations can be evaluated by means of the technique proposed by Hägglund (ODT, 1995) by using zero crossings of the error signal (e = PV- SP) and calculating the integrated absolute error (IAE) between successive zero crossings. A first characterization of oscillations can be performed by means of Auto Correlation Function (ACF, Thornhill et al., 2003). Advances and new directions in oscillation detection and diagnosis are widely reviewed in Thornhill and Horch (2007). Once tuning is detected as cause of low performance in the loop, model free retuning techniques are quite appealing: see for instance Shamsuzzoha and Skogestad (2010). Recently Marchetti et al. (2013) proposed a retuning technique for cascade loops based on oscillation trends, which does not require any additional information on the process.

The state of the art and advanced methods for the diagnosis of valve stiction (static-friction) has recently found a comprehensive compendium in the book edited by Jelali and Huang (2010), where eight different techniques are illustrated and compared on a benchmark of industrial data. The possibility of diagnosing stiction is included in several closed loop performance monitoring (CLPM) systems, proposed nowadays by major software houses.

Being the valve position (MV) usually not available, a still open problem is the quantification of stiction, by predicting MV from PV and OP values. Quite a lot of techniques appear in literature in the last years: Choudhury et al. (2008), Jelali (2008), Karra and Karim (2009), Farenzena and Trierweiler (2012). The reliability of these techniques is still under exploration, as showed by Qi and Huang (2011), Bacci di Capaci and Scali (2013).

In new design plants, the adoption of intelligent instrumentation, valve positioner and field bus communication systems increases the number of variables which can be acquired and analyzed by the monitoring system. This fact enlarges the potentialities of performing a more precise diagnosis of valve problems. Cause of malfunctioning in pneumatic valves, by far the most used in process control, are not only limited to the presence of stiction (and related problems, as deadband, hysteresis, backslash), but can also include other causes (changes in spring elasticity, membrane wear or rupture, leakage in the air supply system). The positioner itself can also be the source of other specific faults which can upset loop performance. All these malfunctions require specific actions to be counteracted by operators. Therefore it is very important to be able to diagnose and separate different sources. Surprising enough, this topic has not yet been addressed in literature; one of the few works is given by Huang and Yu (2008).

In the last years, ENEL (the largest Italian Electric company) started a project of advanced diagnostics, in order to enhance the possibility of accurate diagnosis of these sources of perturbations. The starting point was the performance monitoring system, already developed at CPCLab of the University of Pisa, based on the 3 classical variables (SP, PV, OP) and denominated PCU (Plant Check Up; Scali and Farnesi, 2010). The first step of this project was devoted to an experimental characterization of anomalies in control valves and was oriented to a fine diagnosis based on additional variables available by intelligent instrumentation. First results are reported in Scali et al. (2011). The present paper is the continuation of this activity, which after experimentation and check, will lead to a new architecture of the performance monitoring system, based on 4 or 6 available measurements.

The paper has the following structure: section 2 describes the experimental plant (pilot scale), its instrumentation and types of reproduced anomalies; section 3 presents the definition of performance indices and the calibration of threshold values; section 4 illustrates the logics of the diagnosis system and a comparison of verdicts based on different variables; section 5 presents results for industrial loops (power plant); conclusions and next steps are reported in section 6.

2. THE EXPERIMENTAL PILOT SCALE PLANT

The Idrolab plant is a pilot scale experimental facility having the general scope of testing new technology to improve efficiency and environmental compatibility of thermoelectric power plants. The specific project regards the development of a new architecture of the automatic system for loops performance monitoring and fault diagnosis (PCU).

Experiments were carried out on the hydraulic module of the plant, which allows water recirculation between two drums (Scali et al., 2011). The presence of bypass lines equipped with control valves and the possibility of acting on pressure and level of the higher drum, allows to carry out experiments in a wide range of operating conditions. By Fieldbus Foundation communication protocol, the control system can collect data from many "intelligent" instruments installed, among which the two pneumatic actuators under test (Fisher Rosemount - DVC5020F type and ABB - TZID type). The pneumatic actuators are coupled to spherical valves which control the water flow rate in recirculation lines.

The positioner of the pneumatic valve acts as an inner control loop on the valve position and allows to speed up the response of the valve. A schematic representation of a Flow Control (FC) loop with positioner is reported in Figure 1.

In addition to SP, OP and PV, commonly available in an industrial FC loop (C_e), DS, P, MV represent the variables made available by the positioner (for a total of 6 variables). The Drive Signal (DS), is the electric signal generated by the inner controller (C_i) which, through the i/p converter, generates the pressure signal (P) acting on valve membrane (P_i), thus determining the position of the valve stem (MV, also called Valve Travel); P_e indicates the process relating MV with PV.

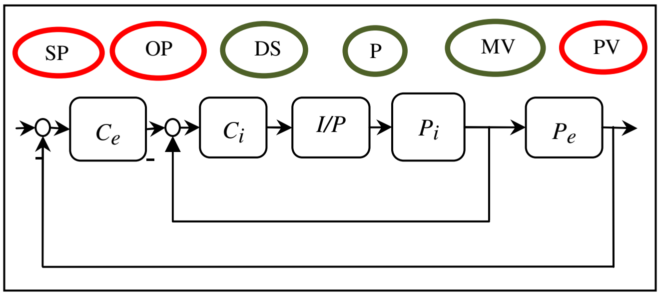

Fig. 1. Block diagram of a FC loop with positioner.

Different problems have been reproduced in experimental valves by means of a modular item mounted on top of them, as shown in Figure 2. This equipment has allowed to reproduce common anomalies: static and dynamic friction, air leakage and i/p converter malfunction. Further details about description of valve problems and the ways these anomalies were reproduced are reported in Scali et al. (2011).

Fig. 2. Picture of the modified control valve (DVC5020F type).

In this second stage of the project, attention was focused on common sources of oscillation in control loops and on common causes of anomaly in industrial valves. The basic idea is to develop the enhanced system by taking into account indications coming from additional variables made available by intelligent instrumentation, thus originating the improved PCU_N, with up to N=6 variables.

Many experiments were performed in the allowed operating range of the valves and of perturbations. Experimental runs were carried out with the valve operating in Travel Mode and in Flow Control Mode (Scali et al., 2011). In Flow Control Mode, the FC loop acts directly on the valve or the Level Control loop acts as primary loop on FC. Runs were carried out by introducing valve anomalies or loop perturbations in the system operating at steady state (no Set Point changes) and repeated applying step SP changes of the flow rate.

Table 1 reports 6 typologies of experiments. They can be considered representative of general behaviour of the system, thus allowing to draw general conclusions. The nominal case N does not present any valve malfunction or loop perturbation. In case D there is an external loop disturbance. In the other cases, malfunctions related to stiction, dynamic friction (jamming), air leakage and i/p converter clogging have been reproduced in the actuator.

Table 1. List of the cases of study.

Case	Description
N	nominal: no valve anomalies or external disturbance
D	disturbance: external perturbation and no valve anomalies
J	jamming: internal dynamics slowed down
S	stiction: valve static friction
L	leakage: imposed on the air circuit tools
M	i/p converter malfunction: nozzle clogging

Different responses in terms of loop and actuator variables (OP, PV, MV, DS, P) to SP change were characterized for the nominal cases and for the faulty conditions (Scali et al, 2011). The availability of MV allows to introduce a key variable: Travel Deviation, which is defined as the difference between real and desired stem position (TD = MV-OP). TD is the most immediate variable for a first distinction between different phenomena. Typical trends of TD in the nominal case and in the presence of different types of malfunction are shown in Figure 3.

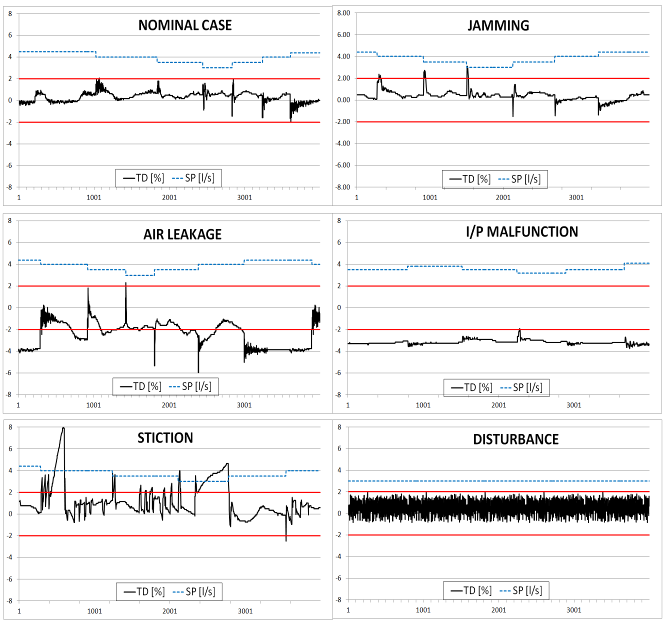

Fig. 3. TD time trends for nominal case and different malfunctions.

The following preliminary qualitative observations can be formulated.

- In the nominal case TD has a mean value close to zero and has only low peaks in correspondence with SP variations. An acceptability band for nominal conditions can be easily set: TDlim.
- Dynamic friction (jamming) shows to be very similar to nominal case and seems difficult to detect.
- Air leakage determines a clear downward shift of the mean value of TD, which lays for a long time outside its acceptability band.
- Malfunction (clogging) of i/p converter shows a quite similar behaviour to air leakage.
- Stiction produces persistent oscillations in TD, even when the SP is constant; TDlim is often trespassed.
- TD oscillations may also be caused by the presence of periodic disturbances (or aggressive tuning controller), but in this case, amplitude peaks are quite small because MV follows OP: this allows to exclude the presence of stiction.

It is worth to say that these observations are fairly general because they involve malfunctioning of single components of the control loop (in particular valves) and therefore their appearance do not depend on the different characteristics of the process (chemical or physical nature).

3. KPI DEFINITION AND CALIBRATION

Data trends have been analyzed with the scope of performing a complete automatic analysis of the actuator using Travel Deviation. The methodology has been overall validated on more than 50 different data sets. Six Key Performance Indices, based on simple metrics of TD, are adopted:

- **I_1**, Significant Oscillation Index: number of times TDlim is exceeded (normalized to 1 hour).
- **I_2**, Percent Time Out: Time percentage of TD out of its acceptability band.
- **I_3**, Mean Travel Deviation: Mean value of TD.
- **I_4**, Integral Travel Deviation: Integral of TD (normalized to 1 hour).
- **I_5**, Absolute Integral Travel Deviation: Integral of TD absolute value (normalized to 1 hour).
- **I_6**, Blockage Index: Numbers of valve stick-slip movements excluding peaks due to SP changes (normalized to 1 hour).

These indices allows a quantitative assessment of the different behaviours between nominal cases and faulty ones. Indices I_3, I_4 and I_5 are defined independently of any other parameters. On the contrary, I_1 and I_2 are based on TDlim, the acceptability band of oscillation of TD. Also I_6 values depend on two secondary parameters which allow to exclude TD peaks caused by set point changes.

Calibration of the threshold values for the actuator KPI and for the additional parameters was performed afterwards. The threshold calibration allows to characterize the nominal behaviour and to recognize different malfunctions. Range of variation of the different parameters have been tested and consequently the values assumed by the KPI for the cases listed in Table 1 have been evaluated. For brevity sake, these results are not reported in this paper. For example, high changes in the values of I_6 were observed and I_1 was always close to zero in nominal cases. Among additional parameters, acceptability band for TD was set to TDlim = 2. Obviously, calibration values may depend on the specific equipment and loop; in particular they depend on control operators sensitivity and their level of acceptable performance. Therefore, calibration thresholds can vary for different applications, but qualitative trends, shown in Figure 3, remain; illustration of case studies and all details can be found in Scali et al., 2010.

Table 2 shows the calibrated values of thresholds for actuator indices. Each actuator index is also associated to one or more valve malfunctions: the symbol "&" means anomalies which affect indiscriminately the index, while "OR" indicates anomalies which are discernible one from the other.

Table 2: Actuator indices: threshold values and malfunctions.

Index	I_i-low	I_i-high	Detectable Malfunction
I_1	5	10	Stiction & Leakage & i/p Malfunction.
I_2	3	6	Stiction OR (Leakage & i/p Malfunction)
I_3	±1	±2	Leakage & i/p Malfunction OR Stiction
I_4	±3000	±6000	Leakage & i/p Malfunction
I_5	3000	6000	Leakage & i/p Malfunction
I_6	5	12	Stiction

The following quantitative observations can be done:

- Stiction is promptly detectable. On the basis of index I_6 and, in addition, by indices I_1 and I_2.
- Air leakage and i/p malfunction are not clearly separable. They act on the same indices, producing, in particular, the same effects on the indices from 1 to 5. Both cause a loss of pressure - directly due to loss of air or due to the difficult opening of the relay - with the consequent move of the valve stem.
- Jamming (dynamic friction) affects mainly index I_1, but this index is sensitive to all other failures. For this reason, this anomaly does not seem detectable by TD.
- Further experimentations based on DS and P could allow to separate air leakage and i/p malfunction.
- This approach ignores simultaneous type of failures which may happen in practice; this scenario is still object of research and experimentation.

The logic for assignment of verdicts does not require any calibration, once threshold values have been set. Obviously, validations and confirmations by plant operators are necessary to check the reliability of the diagnosis (Scali et al., 2010).

4. ACTUATOR STATE and NEW DIAGNOSTIC SYSTEM

The logic of the new PCU, which performs actuator analysis, will be presented. Even with the limitations highlighted before, it was possible to set a new logic which allows to:

- assess the operating condition of actuators with three performance grades:
  1) Good (no problems);
  2) Alert (incipient deterioration);
  3) Bad (poor performance).
- indicate the cause when performance is not acceptable (level 2 or 3).

With reference to Table 2, two threshold values (I_i-low and I_i-high) were established:

- below I_i-low value, the performance is considered similar to the nominal case (good);
- above I_i-high value, the performance is poor;
- between the two values, I_i-low ÷ I_i-high, there is the area of incipient deterioration.

The verdict of actuator state is based on actuator indices compared with their threshold values. The logic follows the combination of the indications reported in Table 3.

Table 3: Verdict of actuator state.

Actuator State	Conditions on Actuator Indices	
GOOD	All the actuator indices good	I_i < I_i-low, for i=1,..,6
ALERT	Almost one index overcomes the low threshold and No indices overcome the high threshold	i : I_i > I_i-low and I_i < I_i-high, for i=1,…,6
BAD	Almost one index overcomes the high threshold	i : I_i > I_i-high

Therefore it is possible to diagnose three causes of valve malfunction:

1. **Stiction**: it can be diagnosed without any doubt.
2. **Air leakage or i/p malfunction**: they can be diagnosed only together.
3. **Generic Malfunction**: includes all causes not directly recognizable but responsible for actuator fault.

The synthesis of the logic about actuator status is reported in Table 4 and illustrated below in the flowchart of Figure 4. All indices contribute to define the actuator state, but only I_3 and I_6 determine the cause of failure.

Table 4. Conditions for the emission of actuator verdict.

Condition	Source of actuator anomaly
Actuator State: GOOD	–
I_3: BAD	Air leakage or i/p malfunction
I_6: BAD & I_3: GOOD or ALERT	Stiction
Actuator State: ALERT or BAD	Generic Malfunction

The proposed logic has been included in the new (advanced) performance monitoring system (PCU_4). Figure 5 shows the architecture of the system. The availability of the MV/TD allows to evaluate the specific KPI indices and to activate a new analysis path oriented to actuator diagnostics (module Act_AIM). Module Act_AIM issues verdicts of state and causes of anomalies of the actuator: Stiction, Air leakage or i/p malfunction and Generic Malfunction. These verdicts are definitive and affect subsequent analyses.

In previous PCU (PCU_3) the only possible path of analysis was oriented to loop diagnostics (now indicated as Loop_AIM) to detect presence of external disturbances or controller tuning problems. As main difference, valve anomalies are detected only indirectly and always classified as stiction. More details about different PCU_3 modules can be found in Scali and Farnesi (2010). In PCU_4, the loop path is activated subsequently to actuator path and some more accurate tests in Frequency Analysis Module (FAM) and Stiction Analysis Module (SAM) are performed.

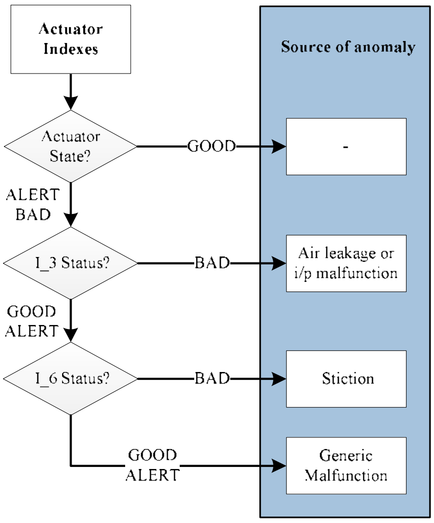

Fig. 4. Logic for the emission of actuator verdict.

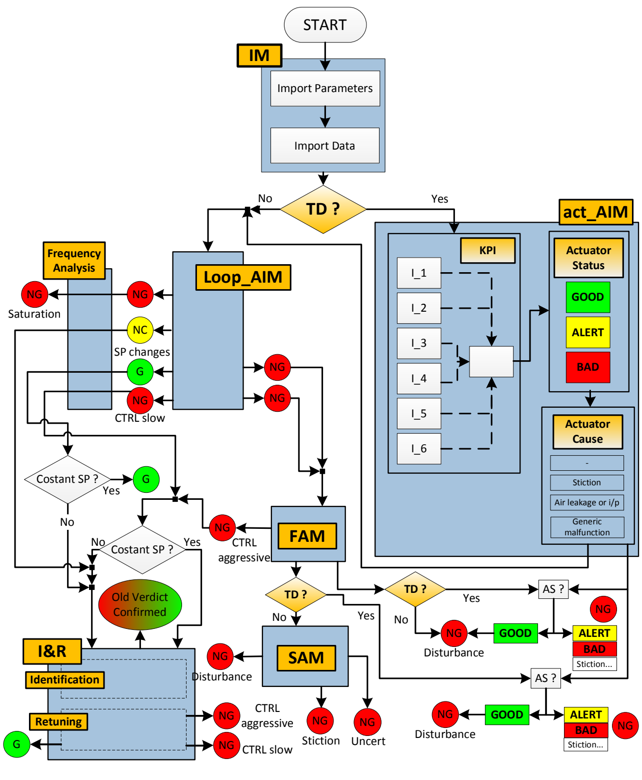

Fig. 5. Schematic representation of the PCU_4 (MV and TD available).

Table 5 shows a comparison of the results between the two releases of PCU system, based on 3 and 4 variables, applied to the typologies listed in Table 1. Some observations follow.

- In all cases (except D) the PCU_3 is not able to recognize any type of malfunction. No significant oscillation is detected because loop oscillation is considered acceptable on the basis of the threshold value assumed for the Hägglund technique (Hägglund, 1995).
- On the contrary PCU_4 is able to diagnose malfunctions in the actuator (not yet visible in the loop) and issues correct verdicts (S, L, M). Therefore indices I_1-I_6 and the logic of verdict emission are properly set.
- Both PCU releases recognize the nominal case (N).
- In case D a disturbance is actually present. The verdict is confirmed by PCU_4, for which the actuator is good and the disturbance is properly indicated in the loop.
- Dynamic friction (case J) is not correctly detected based on previous considerations.
- For cases L and M, PCU_4 detects properly an actuator fault, but it is unable to distinguish between air leakage and i/p converter malfunction. These two causes are detected only together and the loop state is good.
- Case S is emblematic: PCU_4 correctly detects valve stiction, while PCU_3 wrongly emits a verdict of good performance.

Table 5. Comparison of results on Idrolab data: PCU_3 vs PCU_4.

	PCU_3	PCU_4	
Case	**Loop Status**	**Actuator Status**	**Loop Status**
N	GOOD	GOOD	GOOD
D	BAD [Disturbance]	GOOD	BAD [Disturbance]
J	GOOD	GOOD	GOOD
S	GOOD	BAD [Stiction]	GOOD
L	GOOD	BAD [Air leakage or i/p malfunction]	GOOD
M	GOOD	BAD [Air leakage or i/p malfunction]	GOOD

It is evident that MV/TD allows a successful diagnosis of malfunctions that are not detectable simply by using OP and PV; that is the actuator analysis implemented in PCU_4 allows to recognize serious malfunctions which otherwise would be hidden by loop dynamics. Analogously, the availability of MV would make stiction quantification an easier problem.

5. VALIDATION ON INDUSTRIAL DATA

The ENEL - La Casella (Piacenza), a combined cycle power plant (4 groups), was chosen as first site for PCU_4 validation. Each independent unit is composed of a gas turbine, a heat recovery exchanger for steam generation and a steam turbine. Control loop regulation is performed by pneumatic valves with positioners.

A whole monitoring and assessment system has been implemented online (PCU_4_GUI). The system performs scheduling of operations, data acquisition directly from DCS via OPC servers, data analysis and display of results on an user-friendly interface. Currently 28 (7·4) critical loops have been configured in the system and analyzed for months.

As results, the system has allowed to assess:

- 21 loops with good performance;
- 7 loops with bad performance (2 affected by external disturbances; 5 with controller tuning problems);
- 19 valves with good performance;
- 9 valves affected by stiction.

For example, the 4 actuators used for the level control of the high pressure (HP) cylindrical bodies have been constantly diagnosed in stiction. These problems have been confirmed directly by plant operators, who observed heavy wear on valve stems during the plant shutdowns. Figure 6 shows time trends for two different loops: a LC loop for HP cylindrical body and a TC loop for methane preheating.

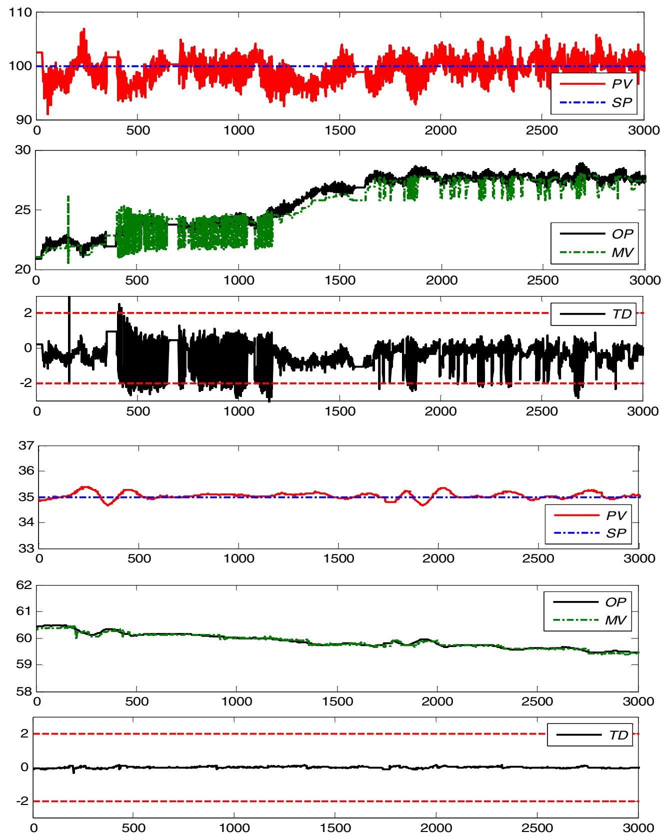

Fig. 6. Time trends for: top) LC loop with valve stiction; bottom) TC loop with good performance.

The LC loop has a valve clearly affected by friction. The TD is particularly oscillating and often trespasses the band of acceptability. Note that also PV is oscillating. The MV is characterized by continuous stick and slip movements. The values of the actuator indices are respectively: I_1=46, I_2=5.6, I_3=-0.47, I_4=-1691, I_5=2413, I_6=120. Therefore the verdict on the actuator is stiction. On the contrary, the TC loop has no significant oscillation and shows good performance both in the loop and in the actuator.

6. CONCLUSIONS

The adoption of additional variables, made available by intelligent instrumentation, allows a more efficient control loops assessment and a more accurate diagnosis of causes. In particular the Travel Deviation, by means of suitable performance indices, is able to detect different types of malfunctioning in pneumatic valves. Performance indices and the logic of assigning performance grades, defined and calibrated on the pilot plant, has been implemented and successfully validated on the industrial plant. Therefore system can be considered reliable in monitoring performance and diagnosing malfunctions. Further improvements are possible by using additional variables, as positioner Drive Signal and i/p converter Pressure; next activity will be devoted to their analysis.

REFERENCES

Bacci di Capaci R., Scali C. (2013): “Valve Stiction Quantification: a Robust Methodology to Face Most Common Causes of Loop Perturbations”; *Chemical Engineering Transactions*, 32, pp. 1201-1206.

Choudhury M.A.A.S., Jain M., Shah S.L., Shook D.S. (2008): “Stiction - Definition, Modelling, Detection and Quantification”, *J. of Process Control*, 18, pp. 232-243.

Farenzena M., Trierweiler J.O. (2012): “Valve Stiction Evaluation Using Global Optimization”; *Control Engineering Practice*, 20, pp. 379-385.

Hägglund T. (1995): “A Control Loop Performance Monitor”, *Control Engineering Practice*, 3, 1543-1551.

Huang X., Yu F. (2008): “A Simple Method for Fault Detection of Industrial Digital Positioners”, *In Proc. of VII WCICA*, Chongqing, China, pp. 6863-6866.

Jelali M. (2008): “Estimation of Valve Stiction in Control Loops Using Separable Last Square and Global Search Algorithms”; *J. of Process Control*, 18, pp. 632-642.

Jelali M, Huang B. (Editors) (2010): “Detection and Diagnosis of Stiction in Control Loops: State of the Art and Advanced Methods”, *Springer*, London (UK).

Karra S., Karim M. N. (2009): “Comprehensive Methodology for Detection and Diagnosis of Oscillatory Control Loops”; *Control Eng. Practice*, 17, pp. 939-956.

Marchetti E., Esposito A., Scali C. (2013): “A refinement of cascade tuning to improve control performance without requiring any additional knowledge on the process”; *Ind. Eng. Chem. Res.*, 52 (18), pp. 6193–6200.

Scali C., Farnesi M. (2010): “Implementation, Parameters Calibration and Field Validation of a Closed Loop Performance Monitoring System”; *Annual Reviews in Control*, 34, pp. 263-276.

Scali C., Marraccini S., Farnesi M. (2010): “Key Parameters Calibration and Benefits Evaluation of a Closed Loop Performance Monitoring System”; *IFAC-DYCOPS 2010*, Louvain (B), pp. 683-688.

Scali C., Matteucci E., Pestonesi D., Zizzo A., Bartaloni E. (2011): “Experimental Characterization and Diagnosis of Different Problems in Control Valves”; Preprints: *XVII IFAC World Congr.* Milano (I); pp. 7334-7339.

Shamsuzzoha M., Skogestad S. (2010): “The Setpoint Overshoot Method: A Simple and Fast Closed-Loop Approach for PID Tuning”; *J. of Process Control*, 20, pp. 1220-1234.

Thornhill N.F., Horch A. (2007): “Advances and new directions in plant-wide disturbance detection and diagnosis”; *Control Eng. Practice*, 15, pp. 1196-1206.

Thornhill N.F., Huang B., Zhang H., (2003): “Detection of Multiple Oscillations in Control Loops”; *J. of Process Control*, 13, pp. 91-100.