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A Performance Monitoring Tool to Quantify Valve Stiction in Control Loops

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Abstract: The paper presents main features of a performance monitoring system, which allows stiction quantification. It implements a methodology which permits one to reproduce the unknown stem position, without requiring any additional knowledge, based only on data normally registered in industrial plants (controller output OP, controlled variable PV and set point SP). A general procedure is proposed to discard data for which quantification is very likely to give wrong indications and to restrict the application to appropriate cases. Simulations show that several sources of perturbations can be eliminated; on the contrary, the presence of external disturbances may alter the reliability of stiction evaluation and then stiction diagnosis techniques must be applied firstly. Results are confirmed by application to industrial valves for repeated acquisitions, in the framework of a performance monitoring system implemented for continuous supervision of control loops and valve maintenance scheduling and checking.

Keywords: Process Control Applications, Performance Monitoring, Valve Diagnostics, Stiction Detection, Stiction Quantification

1. INTRODUCTION

Control loop performance assessment has been recognized as an important factor to improve profitability of industrial plants. In the last years many techniques have been proposed to allow performance evaluation from routine recorded data and several software packages appeared on the market and are now used as monitoring tools.

A control loop performance monitoring system should be able to detect poor performing loops and to indicate different causes, then suggesting appropriate moves to apply on the plant. Main distinction is among external perturbations, controller tuning and valve problems: for this reason, techniques able to characterize different sources have been proposed. Certainly valve stiction (static friction) is one of the most common causes of performance degradation (Jelali and Huang, 2010).

In Figure 1, the 4 main variables of a control loop are indicated. Set Point (SP), Controlled Variable (PV) and Controller Output (OP) are usually recorded, while valve stem position (MV) is not available in general.

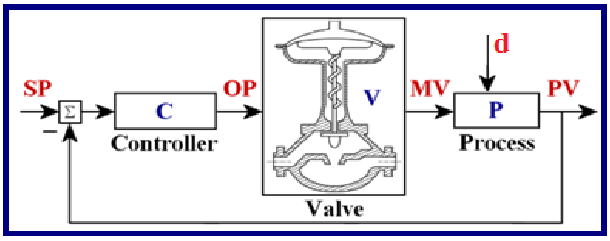

Fig. 1. The reference scheme for a control loop.

The knowledge of MV would allow an easier detection of the presence of stiction because the linear relationship MV(OP) in a valve without stiction, changes to a parallelogram shape in the presence of stiction (see Figure 2).

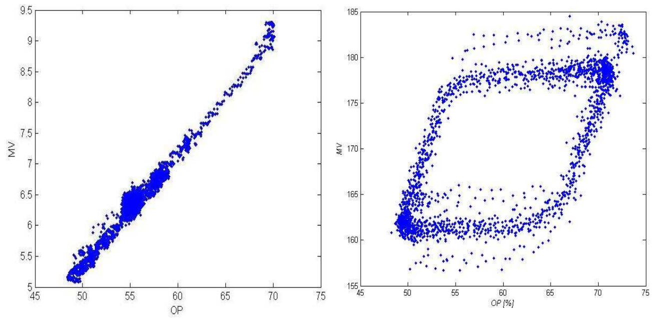

Fig. 2. MV(OP) plots: left): non-sticky valve; right): sticky valve.

When the plant is equipped with valve positioners and advanced communication systems (as Field Bus), the task is even easier: not only stiction can be detected, but also other causes of malfunction can be indicated (for instance: air leakage, I/P converter troubles, etc.); details can be found in Scali et al. (2011), Bacci di Capaci et al. (2013).

On the contrary, when MV is not available, the presence of stiction has to be diagnosed by referring to PV, OP and SP. A detailed illustration and a performance comparison of the most recent techniques of stiction detection, on a large benchmark (93 loops) of industrial data, is reported in Jelali and Huang (2010). As conclusions, this problem can be considered almost solved, even though it cannot be expected that different stiction diagnosis techniques give always the same results once applied on industrial data.

On the contrary, stiction quantification must be considered still an open issue (Jelali and Huang, 2010). The knowledge of the value of stiction is very important in order to follow its evolution in time, to compare with acceptable thresholds and to schedule and check valve maintenance. In addition to techniques, as Choudhury et al. (2006), which give an estimate of *apparent* stiction, methodologies which quantify the parameters of a data-driven stiction model and predict MV signal are much more effective: Srinivasan et al. (2005), Choudhury et al. (2008), Jelali (2008), Karra and Karim (2009), Romano and Garcia (2011), Farenzena and Trierweiler (2012). The main difficulty of stiction quantification is that the *true* value of stiction is not known in industrial data (it may be known in *ad hoc* experiments or in simulations); therefore, the validation of a proposed technique on a single set of industrial data can be incomplete. This is confirmed by the fact that different quantification techniques can strongly disagree when applied on the same benchmark of industrial data (Chapt.13 in Jelali and Huang, 2010). Therefore, the reliability of stiction detection and quantification techniques is still under exploration, as showed by Qi and Huang (2011) and Srinivasan et al. (2012).

The possibility of diagnosing stiction is included in several systems of closed loop performance monitoring (CLPM), proposed nowadays by major software houses. To the best of the authors' knowledge, no commercial tool performs stiction quantification, object of this contribution.

The paper is organized as follows: in Section 2 the proposed method for stiction quantification is illustrated, while the presence of disturbances is investigated in Section 3; Section 4 illustrates the new tool of performance monitoring and stiction quantification; Section 5 presents results for some industrial loops; conclusions and further work are reported in Section 6.

2. THE PROPOSED METHOLOGY

In the proposed stiction quantification technique, the control loop is modeled by a Hammerstein system (Figure 3, top). About stiction modeling, a comprehensive activity has been performed by Choudhury et al. (2005), Kano et al. (2004) and He et al. (2007), who developed data driven models, preferred for their simplicity to more accurate physical models (Karnopp, 1985). Kano model is adopted to describe the non-linear valve dynamics and an ARX (AutoRegressive model with eXternal input) model describes the linear valve and the process dynamics.

The relation between the controller output (desired valve position) OP and the real valve position MV is described in three phases (Figure 3, bottom):
1. Block: MV is steady and the valve does not move, owing to static friction force (deadband + stickband, *S*).
2. Jump: MV changes abruptly because the active force unblocks the valve, *J*.
3. Motion: MV changes gradually, only dynamic friction force can possibly oppose the active force acting on the valve diaphragm; the valve stops again when the force generated by control action decreases under stiction force.

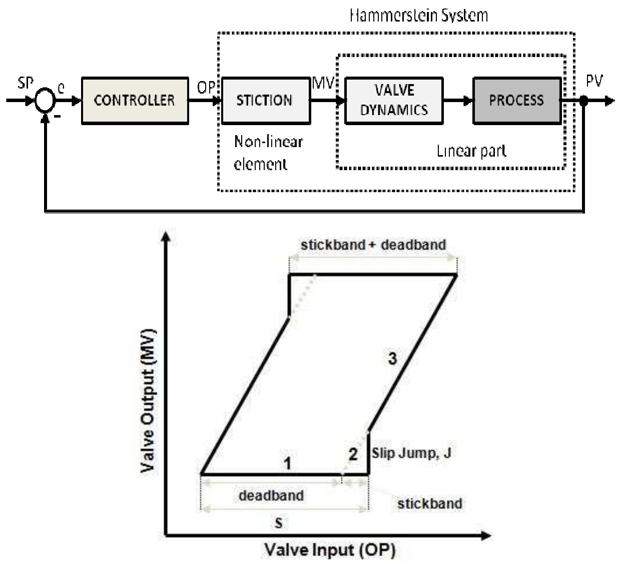

Fig. 3. Top): Hammerstein system; bottom): valve stiction modelling.

Valve stiction produces an offset between PV and SP and causes loop oscillation because the valve is stuck even though the integral action of the controller acts and increases the pressure. In case of Flow Control loop, the fast dynamics allows one to approximate MV(OP) with PV(OP) plot. It is worth saying that the value of *J* is critical to originate limit cycles (Choudhury et al., 2008), but, while *S* is easy recognizable, it is hard to detect *J* in industrial data, owing to its small value and the presence of field noise (Figure 2, right).

The proposed stiction quantification technique is based on a grid search (see Figure 4), method which is simple and mathematically robust. Even though computation times can be longer with respect to other techniques, that does not represent a limitation, as the technique requires data registered for hours, the phenomena of wearing in valves occur slowly (weeks or months) and the valves maintenance usually occurs periodically (on the occasion of plant shutdown). Only a brief description of the proposed methodology is presented here; further details can be found in Bacci di Capaci and Scali (2014).

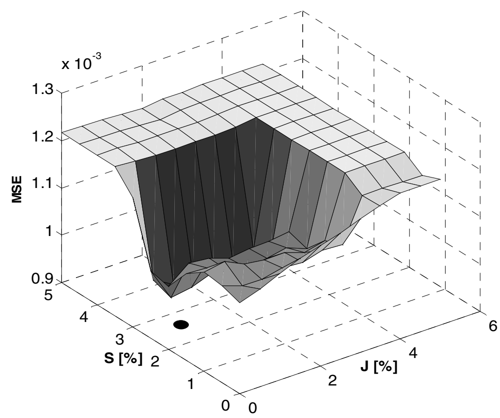

Fig. 4. Grid search for stiction parameters.

A grid of the two stiction parameters *S/J* is built (Figure 4) and MV is generated from measured OP using Kano model. Another grid of possible process time delay is performed. For every possible combination, the ARX model is identified in linear least-squares sense, based on MV and measured PV. The objective is to maximize a fitting index related to the mean-squared error between measured and predicted PV.

As illustrative example, in Bacci di Capaci and Scali 2014, results for a simulated control loop were presented and threshold values for the cited indices were calibrated. Results have general validity, as verified by numerous simulations; different process models and values of stiction parameters were applied. As conclusions, it has been confirmed that the proposed methodology is able to give a correct stiction estimation when valve stiction is the only source of oscillation. The procedure is still correct in case of set point variations and incorrect tuning, with or without the presence of stiction.

On the contrary, in the presence of disturbances, the methodology may give wrong estimations of stiction. The negative effects of disturbances on stiction quantification are illustrated in the next section.

3. STICTION QUANTIFICATION IN THE PRESENCE OF DISTURBANCES

A control loop is simulated: the process P is described by a First Order Plus Time Delay (FOPTD) transfer function and the controller C has PI algorithm with Closed Loop Ziegler-Nichols tuning. Sampling time is set to 1 second. Valve stiction is described with Kano model. This loop is a specific case study, but the results have absolutely general validity: other process models were used and different values for stiction and disturbance parameters were applied; they are not reported for sake of brevity.

$$P = \frac{1}{10s+5}e^{-5 \cdot s};\; C = 1.73\left(1+\frac{1}{14.25s}\right);\; S = 4;\; J = 1; \quad (1)$$

Three simple cases study of simulation are illustrated below:

- In case 1 valve stiction is the only source of oscillation.
- In case 2 the same valve stiction acts with external disturbance: a sinusoidal input with a frequency of 0.2 rad/s and amplitude of 1.
- In case 3 the same valve stiction acts with a higher disturbance: a sinusoidal input with a frequency of 0.05 rad/s and amplitude of 5.

In case 1, the proposed method perfectly succeeds: it gives a good stiction estimation (S=4.01; J=0.85) and an accurate MV prediction (compare Figure 5). In case 2, the amplitude and frequency of the disturbance do not alter too much stiction quantification (S=3.95; J=1.47) and the estimation of MV is still effective (Figure 6, top). On the contrary, in case 3 the external disturbance significantly degrades stiction estimation (S=0.56; J=0.05) and prediction of MV is really inaccurate (Figure 6, bottom).

Therefore the proposed stiction quantification methodology is confirmed to be able to give a correct stiction estimation when stiction is the only source of oscillation. On the contrary, in the presence of external disturbances, the methodology may give wrong stiction estimations.

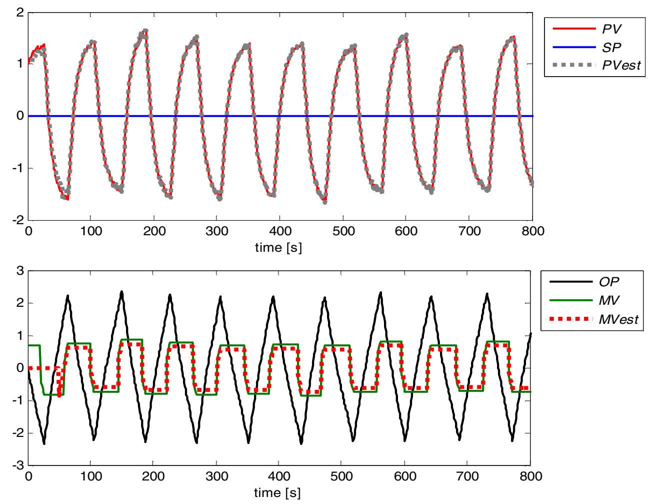

Fig. 5. Only valve stiction: good prediction of MV.

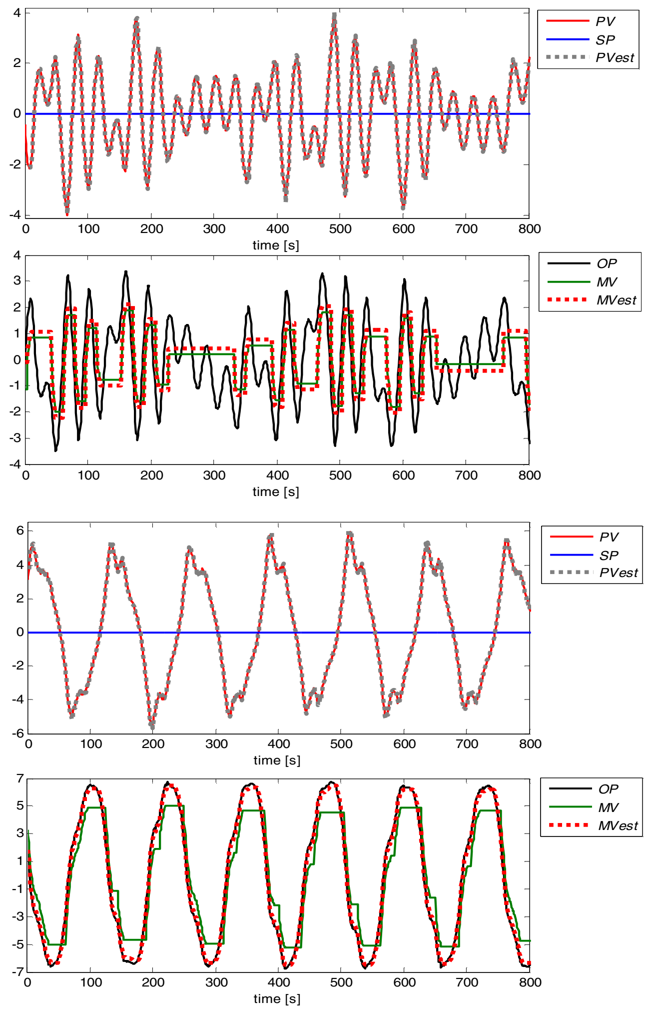

Fig. 6. Sticky valve + external disturbance: prediction of MV; top) good, for case 2; bottom) inaccurate, for case 3.

In Bacci di Capaci and Scali (2014) was proposed to used an unique stiction detection technique (the relay-based, Rossi and Scali, 2005). In the perspective of industrial applications, the suggestion is to adopt more different techniques of stiction diagnosis and to apply the procedure of quantification only when stiction is clearly detected. More details about this point are given in next section where the monitoring system is described.

4. THE PERFORMANCE MONITORING TOOL

The proposed stiction quantification methodology has been included in the new architecture of the control loop performance monitoring system PCU (Plant Check Up). Figure 7 shows the architecture of the system, while the new structure of the module devoted to analysis of stiction (diagnosis + quantification) is reported in Figure 8.

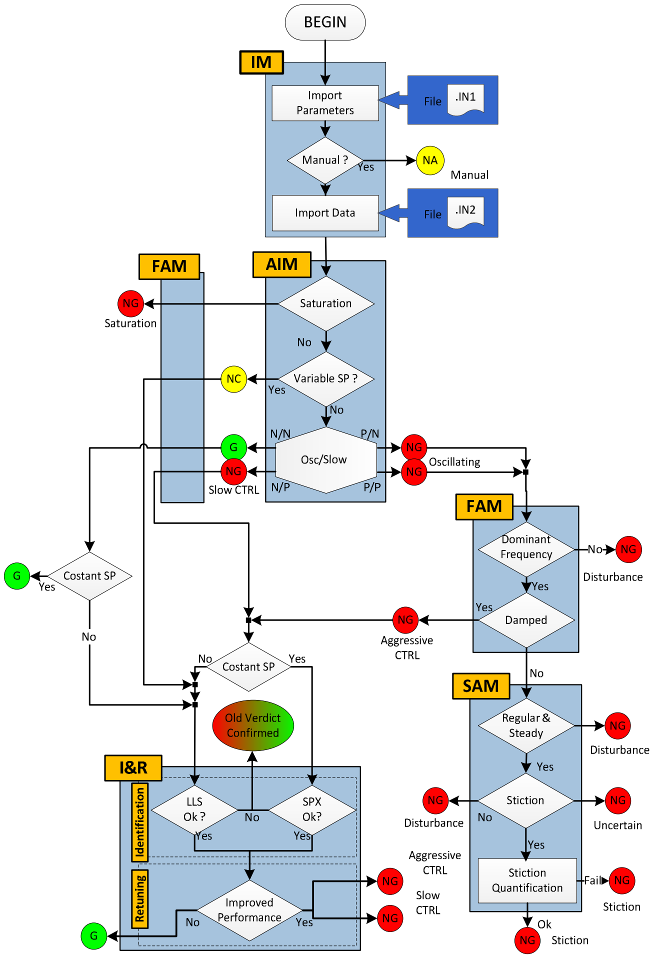

Fig. 7. Schematic representation of the new PCU system.

A full description of the previous version of PCU is reported in Scali and Farnesi (2010); a synthesis is reported below.

The Initialization Module imports parameter values from DCS and performs a first check on loop status; if the quality of the data is not good, or a change of configuration is detected, or the valve is operating manually, the analysis stops. In these cases, the loop receives a (definitive) label (NA: Not Analyzed) and the analysis is stopped. Otherwise, all recorded data are imported and performance analysis begins.

The Anomaly Identification Module performs a first assignment of performance with verdicts: such as G (*Good*), NG (*Not Good*). Loops subject to excessive set point changes (amplitude or frequency) are temporarily labelled as NC (*Not Classified*) and sent to the identification module (I&R). For loops not in saturation, after a data pre-treatment, tests to detect oscillating or sluggish loops are executed; these tests refer to the Hägglund approach (Hägglund, 1995; 1999), with suitable modifications of internal parameters, based on field calibration (Scali et al., 2010). In the case of both tests resulting negative, the loop is classified as well-performing and a definitive label G is assigned. Slow loops can only be caused by the controller: therefore they receive a NG label and are sent to the Identification and Retuning Module (I&R). Oscillating loops can be caused by aggressive tuning, external disturbance or valve stiction: for this reason, they are primarily sent to FAM, for a frequency analysis.

The Identification & Retuning Module accomplishes process identification and, if successful, controller retuning and evaluation of performance improvements. It receives from the AIM module loops with constant SP labelled as NG (Not Good) caused by improper tuning and loops labelled as NC (Not Classified) with variable SP. The two possibilities of constant and variable Set Point are treated differently, the second case being typical of secondary loops under cascade control.

The Frequency Analysis Module has the scope of separating irregular oscillations from regular ones on the basis of a power spectrum which computes dominant frequencies; irregular loops are labelled NG, without any further enquiry about causes. Regular loops with deteriorating oscillations are sent to the I&R Module, otherwise - in the case of loops showing permanent oscillations - to the SAM for stiction/disturbance detection.

The Stiction Analysis Module analyses data of NG oscillating loops and performs different tests to detect the presence of valve stiction and to quantify its amount. Following previous results and considerations about the effect of external disturbances, this module has been significantly changed (Figure 8).

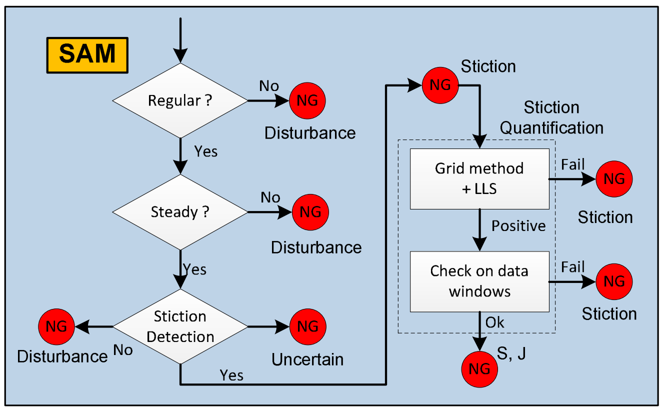

Fig. 8. Flow diagram of the Stiction Analysis Module.

Two techniques to detect significant loop oscillations are firstly applied. Regularity factor r (Thornhill et al., 2003) and decay ratio R_{acf} (Miao and Seborg, 1999) of autocorrelation function (ACF) of the control error are calculated. If the control loop is considered to not oscillate regularly and steadily, the procedures is stopped, because it assumed that non-substantial stiction is present.

About stiction detection, tests consist in the application of four techniques: the relay-based fitting of values of the controlled variable (PV) (Rossi and Scali, 2005), the improved qualitative shape analysis (Scali and Ghelardoni, 2008), the Cross-Correlation (Horch, 1999), which is the simplest (and probably most widely used) test, and the Bicoherence (Choudhury et al. 2004), which allows to put into evidence non-linear characteristics of loop data. The appropriate technique is automatically selected by the system, as well as the "weight" to be assigned to the different techniques, depending on the type of loop.

Final verdict takes into account indications coming from different techniques and from other auxiliary indices: the cause *Stiction* or *Disturbance* is assigned to the exit loop in cases of strong evidence; otherwise the cause is *Uncertain*. The stiction quantification procedure (described in Section 3) is applied only to loops clearly indicated as affected.

To increase the reliability of stiction estimations, data can be divided into sets and the method can be applied separately. The appropriate number of data sections depends on the whole data length; in general, at least 4-5 periods of oscillation are needed. For each data window, a stiction model and a linear model are identified. Then, a comparison of the data windows is performed using two specific indices, which separately evaluate deviations between non-linear and linear models (Bacci di Capaci and Scali, 2014).

Note that the screening by means of diagnosis techniques and the check on the indices of models deviation are not sufficient to assure always an exact diagnosis and an accurate estimation of stiction, but the number of wrong evaluations can be significantly reduced, as reported in the next section.

5. APPLICATION ON INDUSTRIAL DATA

The availability of industrial data is made possible by referring to archives built in the last years of operation of the PCU system on refinery units.

A total of 62 control loops have been examined; each loop underwent repeated acquisitions and received more indications of presence of stiction. The main difficulty about stiction detection and quantification on industrial data is that the *true* position of valve stem MV and the *true* value of stiction are not known. Therefore, to validate the new tool able to quantify stiction, the procedure has been repeated for different acquisitions in order to follow the evolution of stiction values in time and to disregard anomalous cases, which appear as outliers.

As illustrative examples, results for two loops are briefly illustrated in the sequel (Figure 9).

For loop #1, the first 4 registrations show oscillations with wide amplitudes, regular and steady; the stiction diagnosis is always positive. Therefore, the proposed methodology can always be applied and estimates large values of stiction. An increasing trend of S parameter is quantified. For loop #2, before valve maintenance, significant oscillation is detected in 5 (out of 7) data sets and significant stiction is detected and estimated in 4 cases. The procedure gives overall reliable results because uniform values of S parameter are quantified, with mean value equal to 4.9 and little deviation of 0.6. As illustrated in previous simulations, the causes of the unreliable (3 out of 7) results might be seen in the presence of perturbations and stiction acting simultaneously.

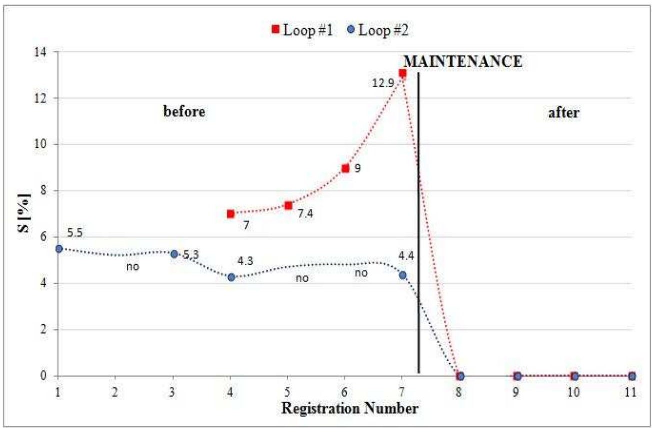

Fig. 9. Trends of stiction before and after valve maintenance.

Data collected after valve maintenance are completely different. The methodology does not detect any significant oscillation and no stiction detection and estimation is performed. The loops are no more oscillating because the valves operate correctly (due to an effective valve maintenance). The removal of stiction in Loop #2 is also confirmed by the comparison of time registrations of SP, PV, OP and estimated PV and MV for a set of data collected before and one set after valve maintenance (Figure 10). Note that loop #2, which operates under MPC with little oscillations in SP, shows good performance because now the error signal is close to zero.

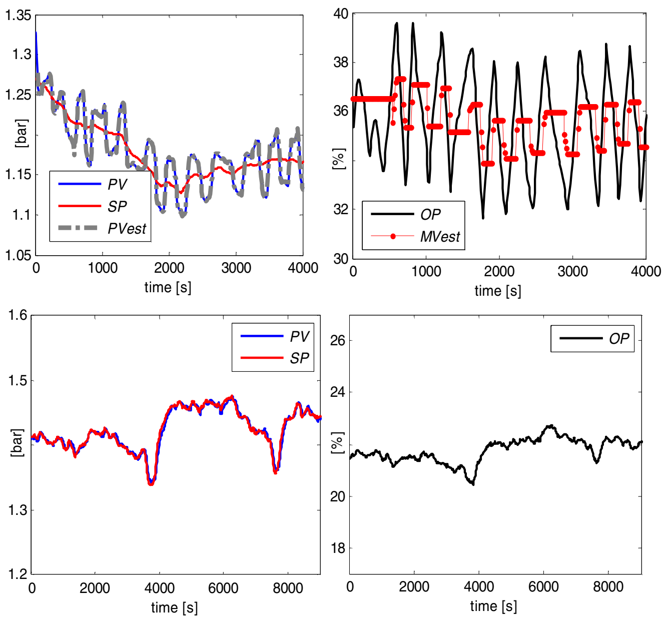

Fig. 10. top): before maintenance; bottom) after maintenance.

As global consideration, the proposed procedure has allowed to issue results which were considered reliable for 43 out of 62 industrial loops examined. The other 19 control loops are cases of unreliable results, for which indices below threshold values are calculated and variable or inconsistent (decreasing over time) trends of stiction are obtained. The main reason of these failures is probably due to the constant presence of perturbations and stiction acting simultaneously.

6. CONCLUSIONS

The procedure for stiction quantification, and its implementation in the performance monitoring system, seems to be a valid tool to check valve stiction and to schedule valve maintenance. The positive aspect is that the procedure allows one to reproduce the unknown valve stem position, without requiring any additional process knowledge, being based only on data routinely registered in industrial plants. The possible drawback seems to be a preliminary assessment of the presence of stiction by means of diagnosis techniques, because the simultaneous presence of external disturbances may alter results. This is a common feature for the majority of stiction quantification techniques and further activity should be devoted to overcome this problem.

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