Implementation and Validation of a Closed Loop Performance Monitoring System

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Abstract: Main features of a performance monitoring systems operating on loops of refinery plants are illustrated together with examples of application and achieved results. The system analyses data recorded by the DCS during routine operation and originates verdicts about performance of control loops; also indications of causes of low performance and different strategies to adopt are given (retuning, valve maintenance, upstream actions). The system architecture is firstly illustrated, with characteristics of modules which accomplish different tasks of data acquisition and transfer, system configuration and priority assignment, performance analysis and verdicts emission, database query and operator support. Examples of field validation are then presented, with illustration of loop performance before and after actions suggested by the monitoring system. A synthesis of main techniques adopted in the system is finally presented.

Keywords: Closed Loop Performance Monitoring, Valve Diagnostic, Identification and Retuning.

1. INTRODUCTION

Closed Loop Performance Monitoring (CLPM) is widely recognized as a primary need in the process industry, as product quality, energy saving, waste minimization depend at a large extent on the efficiency of the control system.

The possibility of evaluating loop performance and being able to diagnose causes of deterioration brings to a direct improvement of plant performance both in the case of base control (SISO PID loops) and in the case of advanced control (MIMO, Optimization), which necessarily relies on good performance of low hierarchy control loops. Different causes of scarce performance, as incorrect tuning of controllers, anomalies and failures of sensors, presence of friction in actuators, external perturbations, should be detected and the right actions to perform should be suggested by the CLPM system.

This is a field where academic research and industrial applications should go ahead in tight contact in order to focus on real problems and to find solutions which are user friendly to be promptly accepted by plant operators. In large scale industrial processes, involving thousands of variables and hundreds of control loops, a monitoring system needs to operate automatically, leaving only key decisions to the operators. Also, results of performance analysis accomplished by the CLPM system should be presented in a very efficient manner to avoid to be seen as an additional work to be performed for plant supervision.

Anyway, even though a completely unattended system can be seen as the optimal solution, the right degree of interaction with plant personnel is of crucial important in the stage of parameter calibration and field validation. Also, the full potential of a CLPM system is fully exploited when the operator has at least a minimum knowledge of performance monitoring issues.

For these reasons, the final system architecture should take into account specific needs and requirements, as well as the skill of the user.

The evolution of academic research can be followed in the abundant literature produced in the last decade: two review papers (Qin, 1998; Thornhill and Horch, 2007) can give a flavour about. Certainly among more important open issues must be considered: the definition of significant performance indices, the development of simple and reliable techniques for automatic detection of causes, the diagnosis of root causes of perturbations in large scale plants. A very active research area is concentrated on methods for automatic diagnosis of valve stiction and many new techniques have been proposed in the last few years. A first comparison can be found in Horch (2006), while Jelali and Scali (2009) compare 11 recently proposed techniques on a benchmark of 93 industrial loops.

The paper illustrates architecture and application results of a Closed Loop Monitoring System recently developed and implemented in an Italian refinery and has the following structure: section 2 presents the overall system, with logic and interaction of different modules performing data acquisition, data transfer and verdicts archiving; section 3 illustrates main features of the system which accomplishes performance analysis and diagnostics; section 4 shows basic features of the Data Base and the query system; section 5 presents some examples of field validation and gives examples of achieved improvements; finally conclusions and next steps are reported in section 6. An appendix will add some details about the techniques adopted for performance analysis.

2. THE SYSTEM ARCHITECTURE

A synthetic picture of the system architecture is depicted in Figure 1, where different modules, their interconnection and physical location are indicated.

The User Module (MU) starts the whole procedure by sending a message to the module of scheduling (MS) about the sequence of plants (and loops) to be analysed (the procedure is repeated periodically). In addition, it allows to see the state of advancement of operations and to send queries to the database (DB) for a synthesis of performance analysis. The user module also permits the configuration of the loops which is the very first step of the performance monitoring process. Loops configuration consists in the assignment of loop name, DCS address, loop info (for instance: single loop or cascade), priorities and constraints of the acquisition. More important loops can have higher frequency of acquisition, cascade loops are acquired simultaneously, loops of the same process unit are analysed in the same data acquisition run.

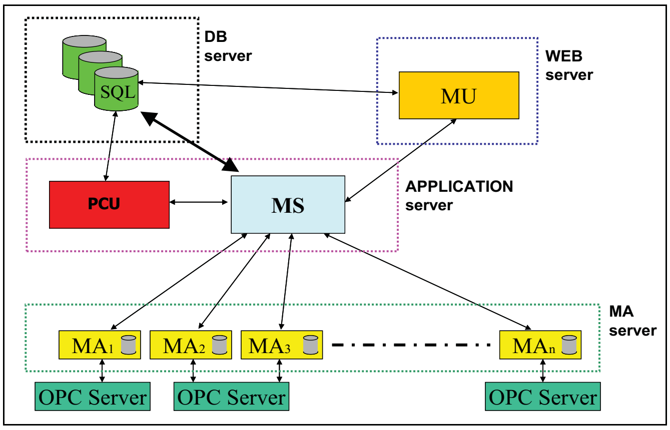

Fig.1: The system architecture

The Scheduling Module (MS), once activated by MU, sends a command to acquisition modules (MAi) which perform physically the acquisition of data from the DCS. For each loop, specific information are transferred to the Data Base (DB) trough MS, such as: loop tag name, controller settings, ranges of controlled variable (PV) and controller output (OP), saturation limits, loop hierarchy (e.g. master/slave of a cascade loop, loops under advanced control), Also information about default, minimum and maximum values for the duration of acquisition and sampling time (ts) are exchanged (default for ts= 10 seconds). Once acquisition is terminated, MS receives from MAi, data files which are sent to the DB input section. It activates the performance analysis accomplished sequentially by the PCU (Plant Check Up) module; finally, verdicts about loop status generated by PCU are transferred to the output section of the DB.

Acquisition Modules (MAi) interact with DCS, from which receive data and updated loop parameters at each sampling time; they act in parallel (up to a maximum number of 7 on a single server) and sequentially on scheduled loops, following priority and constraints indicated by MS. During the acquisition, the quality of each single datum and the change of status (man/auto, cascade open/closed) is checked and a flag is activated. In addition a first analysis is performed locally: mainly, the duration may be increased from the default (2 hours) to the maximum value (8 hours) in order to get a significant number of cycles in the case of very slow oscillating loops.

More about the PCU and DB modules are reported in next sections.

3. THE PCU MODULE

The PCU module contains the intelligence of the performance monitoring systems: it analyses each loop sequentially, interacting with the MS and with the DB from which receives raw data and to which send verdicts. A schematic representation is reported in Figure 2, where main steps and a simplified logical flow of data analysis modules are indicated. Further details about basic techniques adopted inside modules are given in the appendix.

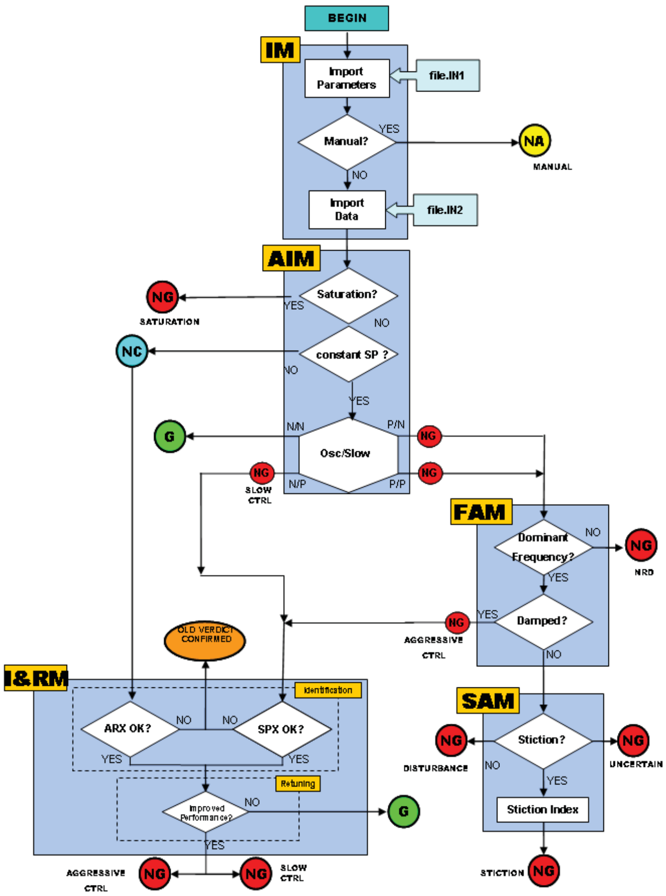

Fig.2: Schematic representation of the PCU module

IM: The Initialization Module imports parameters values from file IN1 and performs a first check about loop status; if the quality of data is not good, or a change of configuration is detected, or the valve is operating manually (info contained in flags activated by MAi), the analysis stops. In this case, the loop receives a (definitive) label (NA: Not Analyzed) and the analysis is aborted. Otherwise, recorded data are imported from the IN2 file and the performance analysis begins.

AIM: The Anomaly Identification Module performs a first assignment of performance with verdicts: as G (*Good*), NG (*Not Good*). Loops subject to excessive set point changes (as amplitude or frequency) are temporary labelled as NC (*Not Classified*) and send to the identification module (I&RM). Valve saturation is checked first and, if detected, the label NG (and the cause) is definitive, without any further analysis (only duration is indicated). 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. In the case of both negative tests, the loop is classified as good 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&RM). 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.

FAM: 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 enquiring about causes. Regular loops with decaying oscillations are sent to the I&R Module, otherwise (loops showing permanent oscillations) to the SAM for stiction/disturbance detection.

SAM: The Stiction Analysis Module analyzes data of NG oscillating loops and performs different tests to detect the presence of valve stiction. They mainly consist in the application of two techniques: the Relay based fitting of values of the controlled variable (PV) (*Rel*; Rossi and Scali, 2005) and the improved qualitative shape analysis (*Ya*$^+$; Scali and Ghelardoni, 2008). The two techniques are recalled in the appendix. Other techniques proposed for stiction diagnosis are also applied, when appropriate. Among them: the Cross-Correlation (*Cxy*; Horch, 1999), which is the simplest (and probably most widely used) test for a first discrimination between stiction and disturbance and the Bichoerence (*Bic*; Choudhury et al. 2005), which allows to put into evidence non linear characteristics of loop data. The appropriate application technique is automatically selected by the system, depending on type of loops, duration of acquisition, etc.. (for instance: Cxy is not used for Level Control, Ya$^+$ is reserved only to Flow Control loops). Final verdict takes into account indications coming from different techniques and from other auxiliary indices: to the exit loop, already tagged NG, the cause *Stiction* or *Disturbance* is assigned in the cases of strong evidence, otherwise the cause is *Uncertain*.

I&RM: The Identification & Retuning Module accomplishes process identification and, if successful, controller retuning and evaluation of performance improvements. It analyses loops tagged NG, owing to controller tuning (that is sluggish or too oscillating responses) and loops tagged NC. The two possibilities of constant and variable Set Point are treated differently, the second case being typical of secondary loops under cascade control. In the case of constant SP, recorded data represent a loop response under disturbance rejection: identification of process dynamics is carried out by means of a Simplex based search procedure (Rossi, 2007; Scali and Rossi, 2009). In the case of variable SP, recorded data represent a loop response under set point tracking: identification is performed by means of an ARX algorithm (Ljung, 1999). In both cases, if model identification is successful, new tuning parameters are calculated according to different techniques, the achievable performance improvement is evaluated by means of suitable upgrading indices and new controller settings are proposed. Otherwise, in the case of impossible identification, the previous assigned verdict is confirmed, without any additional suggestion.

To conclude this synthetic illustration, after the performance analysis by means of the PCU module, every loop is classified as:

- NA (Not Analysed): Manual valve, invalid data acquisition, change of loop configuration;

- NC: (Not Classified): impossible identification and no preliminary verdict;

- G (Good Performing);

- NG (Not Good performing): with an indication of cause (*saturation*, *sluggish, too oscillating, stiction, external disturbance*), or without indication for the cases of irregular disturbances or uncertainty between stiction and disturbance in the SAM.

As distinctive features of the PCU performance monitoring system, the following can be pointed out:

1) it is open to the adoption of new diagnosis techniques; once the algorithm has been built and checked in simulation, it is tested on archived and recent plant data: improvements of reliability of issued verdict lead to updating of algorithms and performance indicators;

2) it has been designed to operate completely unattended and for this reason a verdict is assigned and causes indicated only in the case of strong evidence; false indications are carefully avoided, at the expense of conservative (too cautious) indications: in case of uncertainty, the verdict is postponed to next data acquisitions;

3) the calibration of values of key and auxiliary performance indicators is made on the basis of operator experience, in order to make verdicts as more homogeneous as possible with their practice.

4. THE DATA BASE ORGANISATION

The Data Base contains all information about each single loop: recorded data, controller parameters, loop configuration and diagnosis performed by PCU (verdicts). The possibility of a fast and efficient consultation from the operator is certainly one of main specifications to be achieved for the success of the whole implementation. Therefore, operators suggestions and requirements are carefully taken into consideration in the design of the Data Base architecture. Some significant features incorporated in the DB management are illustrated in the sequel.

1) Analyzed loops and issued verdicts for a group of plants (or all of them) at a certain date, can be immediately summarized on the screen and this allows a first evaluation of loop status, that is the total number of good performing loops, causes of scarce performance, loops in manual, reasons for invalid acquisition etc.. (Figure 3).

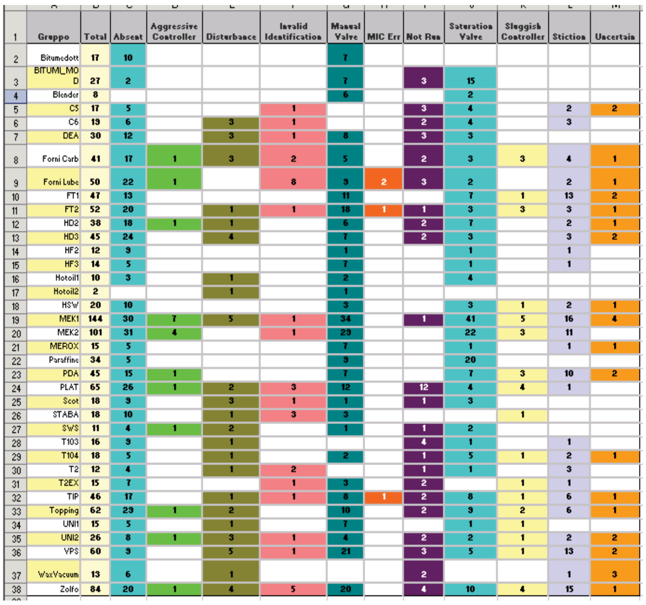

Fig.3: Global picture of all plants monitored at a certain date, with indication of loop status

2) The same type of visualization can be produced for a group of plants (or a single plant) for acquisitions repeated in a desired interval of time, thus allowing a first indication about the trend of loop performance (Figure 4).

Fig.4: Global performance of a single plant for repeated acquisition at different dates

3) All plant loops at a desired date can also be visualized with individual verdicts (Figure 5).

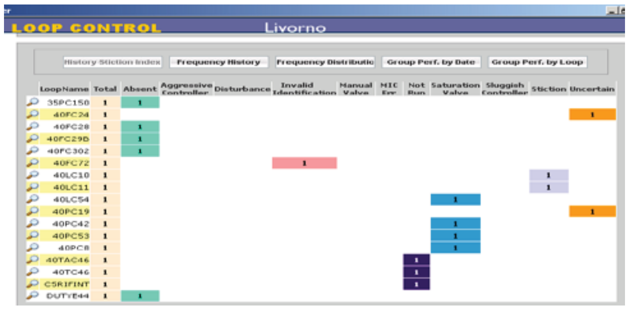

Fig.5: Single plant loop performance at a desired date

4) Single loop performance can be easily investigated, by means of plots and significant performance indices. In the case of successful identification of a loop with incorrect tuning, the trends of SP, PV, OP variables show possible improvements and required control effort with best tuned PI(D) controllers (Figure 6). On this basis (together with values of upgrading indices which allow a quantification of improvements (shown in a separate page), the operator can take a decision about the opportunity of a controller retuning.

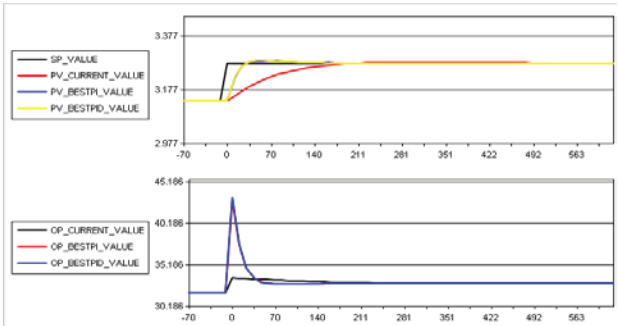

Fig.6: Screenshot for a loop with incorrect tuning

5) In the case of a loop affected by valve stiction, the trends of loop variables, the value of a Stiction Quantification Index (shown in a separate page) allow to evaluate at a glance the situation of the loop (Figure 7). This can be further confirmed by watching the PV(OP) movie (see Figure 11).

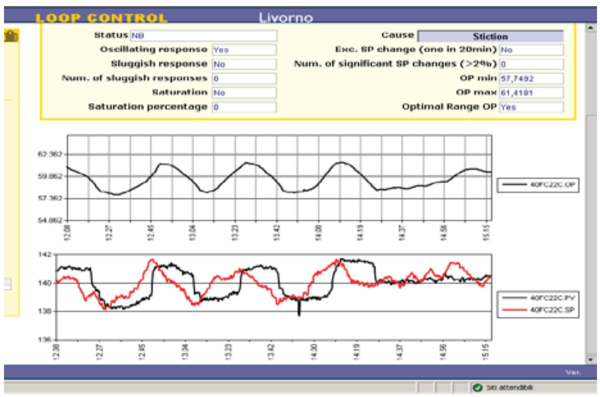

Fig.7: Screenshot for a case of valve stiction: time trends of OP, SP, PV.

7) The loops history can be easily tracked: in the case of a confirmation of issued verdicts, indications for proper actions on the loop can be decided (tuning, valve maintenance, upstream action); an example for a case of

confirmed verdict with increasing stiction in the last four data acquisition is reported in Figure 8.

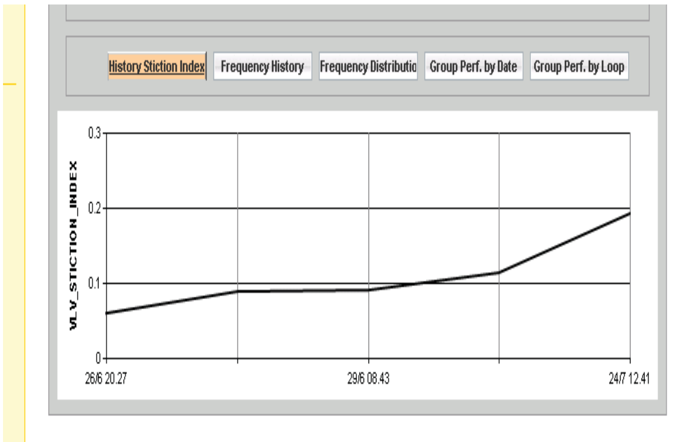

Fig. 8: Loop history for a case valve stiction

4) Many other features allow easy access to more information; for instance: frequency analysis of different oscillating loops and the comparison of dominant frequencies allows to focus on loops possibly affected by the same root cause of oscillations. Other auxiliary performance indexes are evaluated and a large variety of reports about loops statistics can be obtained right way.

5. FIELD VALIDATION

Field validation is the key step of the monitoring system implementation. As first, it allows a direct confirmation of verdicts emitted after loop data analysis, while all indications illustrated in previous section must be considered mere “predictions”, i.e. based on identified models, techniques results and values of performance indices. As second point, this is the step where the operator can give indications for the final calibration of threshold values of performance indices and get confidence about the reliability of verdicts issued by the system. Few illustrative examples are reported in the sequel; more than 600 loop acquisitions were checked during the monitoring system validation.

1) Loop xxFC01 (PI control, Constant Set Point). The verdict from AIM and I&RM modules is NG, indicating as cause: sluggish controller. The identification is successful and the old settings ($K_c=1$, $T_i=0.65$), should be changed to new ones: $K_c=0.49$, $T_i=0.13$. An increase of integral action is then suggested; the upgrade index based on the model (see appendix) is: $\Phi=0.476$. In this case (single FB loop), it is possible to check directly the predicted improvements: a moderate increase to SP has been given by the operator with old settings, followed by a decrease with new settings. The improvement is evident from Figure 9 (the small amplitude and high frequency oscillation represents an unidentified perturbation present in the plant) and the upgrade index evaluated from plant data is $\Phi'=0.573$. This application suggested to reduce the threshold for the index Φ^0 to 0.40 (initially Φ^0 was assumed equal to 0.50).

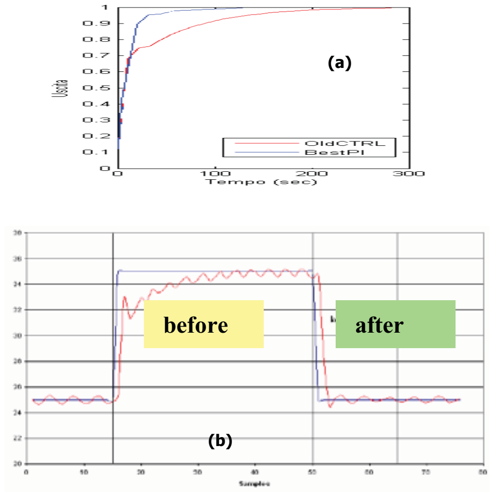

Fig.9: Response to a SP change: model prediction (a), field validation before and after retuning (b)

Loop xxFC02 (PI control, Variable Set Point). Also in this case the verdict from AIM and I&RM modules is NG, owing to sluggish controller; old settings: $K_c=0.8$, $T_i=0.7$; new settings: $K_c=2.6$, $T_i=0.72$. A strong increase of the proportional constant is proposed in this case, while the integral time constant does not change much; the upgrade index based on the model is now $\Phi=0.487$. Being a secondary loop under cascade control, in this case it is not possible to give arbitrary set point changes during plant exercise. Moreover, being suggested a large increase of the gain K_c, the operator applied a gradual increase of gain: 0.8, 1.2, 1.6, 2.6. The corresponding improvement of response in set-point following is evident from Figure 10; the upgrade index evaluated from plant data for increasing value of K_c, is now evaluated by the index (see appendix) $IQI = 0.038, 0.78, 0.85, 0.94$, to confirm the performance improvement.

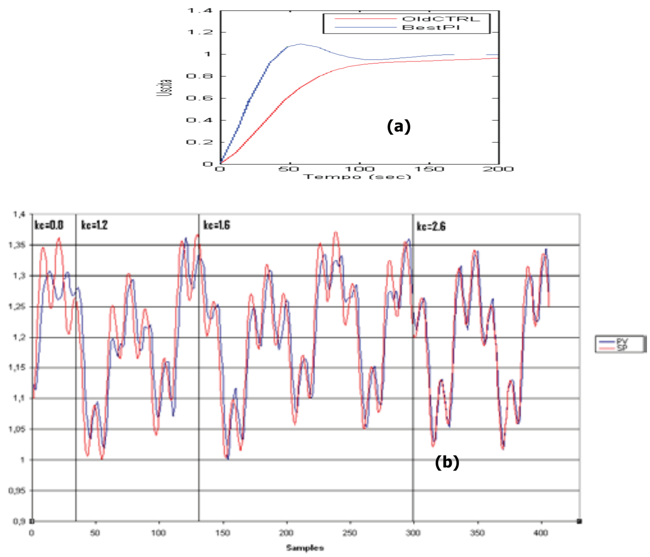

Fig.10: Response to a SP change: model prediction (a), field validation for increasing values of the gain K_c (b)

Loop xxFC08 (PI control, slow varying Set Point). This loop has been repeatedly indicated as affected by stiction in several analysis. The values of the Stiction Quantification Index increased from 0.07 to 0.195 in about one month. The presence of stiction is clearly recognizable by the PV and OP shapes (close to square waves and triangles, respectively in Figure 11a). Moreover, the plot of PV(OP), which can be seen as a movie on the screen, shows evident stiction characteristics (Figure 11b); because in this case (FC loop), the controlled variable PV is proportional to the valve opening MV. Valve maintenance brought to an improvement of performance and a sharp decrease of the stiction index (Figure 12).

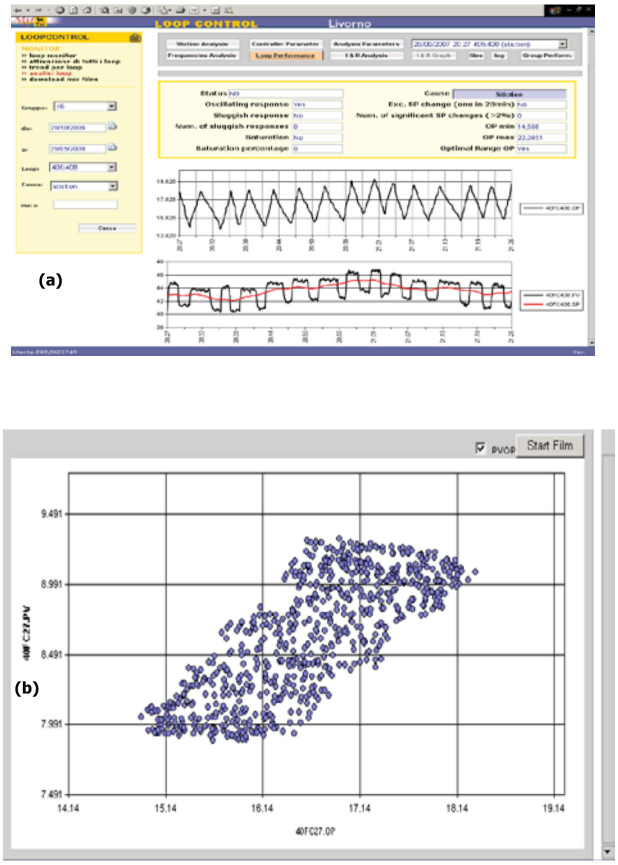

Fig.11: Validation of a loop affected by valve stiction: (a) SP, PV, OP trends; b) PV(OP) movie (FC loop)

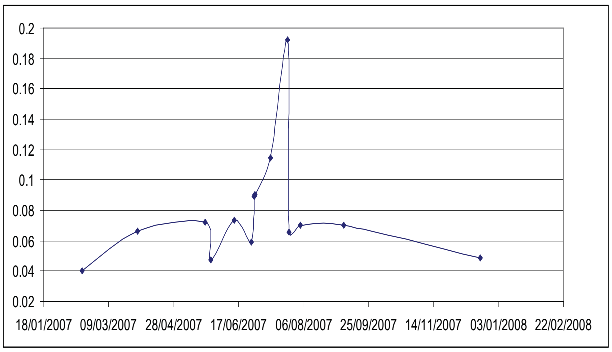

Fig.12: Time trend of the Stiction Quantification Index before and after valve maintenance

6. CONCLUSIONS

The Closed Loop Performance Monitoring system described in the paper has been developed and built with tight cooperation between university and plant personnel. The role of plant operators has been crucial for the success of the implementation, mainly in the calibration of threshold values for key performance indices and in the definition of specifications of the Data Base query system for an efficient analysis of loop performance. This fact has brought to a final version of the system "customized" on user requirements.

The design specifications for a "completely unattended" system forced to the adoption of conservative (default) values for key performance indices and, as a consequence, verdicts are emitted only in case of strong evidence, leaving a certain number of uncertain/unclassified cases. In the stage of assistance to the project, loop analysis was repeated for these cases by changing threshold values, allowing to explain many of them, thus confirming the advantages of a deeper involvement of plant personnel.

The flexibility of the system is an important feature, allowing different levels of interaction with the operator: from the lowest (analysis of periodical performance reports issued by the system) to the highest (actions on loops labelled as poorly performing). The inspection of these loops allows to focus on anomalous situations, both in the case of complete verdicts (cause indicated), and in the case of incomplete diagnosis for a deeper analysis based on process knowledge.

After implementation on a selected plant (about twenty loops), followed by field validation, it has been applied on about fifteen plants, featuring several hundreds loops. A further validation is carried on with the scope of a systematic evaluation of obtained benefits in the perspective of implementation on other group refineries.

Appendix A. ADDITIONAL DETAILS ABOUT PCU

The PCU (Plant Check Up) is the engine of the performance monitoring system and accomplishes an analysis of loop data in order to evaluate performance and to diagnose causes. Some more details are given here about techniques for stiction diagnosis, identification retuning and performance improvement evaluation. Necessarily, only a synthetic illustration is reported here; full details can be found in the references.

A.1 Stiction Diagnosis

Two techniques are mainly used for this scope: the Relay fitting of PV values (*Rel*; Rossi and Scali, 2005) and the improved qualitative shape analysis (Ya^+; Scali and Ghelardoni, 2008).

The *Rel* technique consists in the fitting of significant half cycles of the recorded oscillation by means of three different models: a sine wave, a triangular wave and the output response of a first order plus time delay under relay control. The last one is able to approximate the square waves shapes generated by the presence of stiction and modified by the process dynamics (Figure 13). Relay and triangular shapes are associated with the presence of stiction, while a sinusoidal shape with the presence of external perturbations. By comparing the error between real and fitted data, an evaluation of the accuracy of approximation and then an indication of the underlying phenomenon can be obtained. Once approximations have been performed, a Stiction Identification Index (S_I) can be defined. Being E_S the minimum square error obtained by the sinusoidal approximation and E_{RT} the one obtained by the better approximation between the relay and the triangular waves, S_I is defined as:

$$S_I = (E_S - E_{RT})/(E_S + E_{RT}) \qquad (1)$$

Here E_S, E_{RT} indicate average values of error over the number of examined cycles. S_I varies in the range [-1; +1]: negative values indicate a better approximation by means of sinusoids, positive values by means of relay or triangular approximations. Values close to zero indicate that the two approximations have similar errors and the procedure gives an uncertain answer: the uncertainty region is defined by $|S_I|<0.21$.

The technique presents some analogies with the Curve Fitting Method proposed by He et al (2007): in this case, assuming that stiction is associated to a square wave shape in MV, a triangular wave shape is looked for as distinctive feature of stiction after the first integrator element of the loop. This means in OP signal (for self regulating processes – no integrators) or in the PV signal (for integrating processes).

The relay method always analyses the PV signal and uses the relay shape as additional primitive. The global fitting procedure is more complex and time consuming, but in all cases the elaboration time is absolutely negligible compared with the duration of data acquisition. Finally, the method can also put into evidence the presence of asymmetric stiction, by comparing S_I values on positive and negative half cycles.

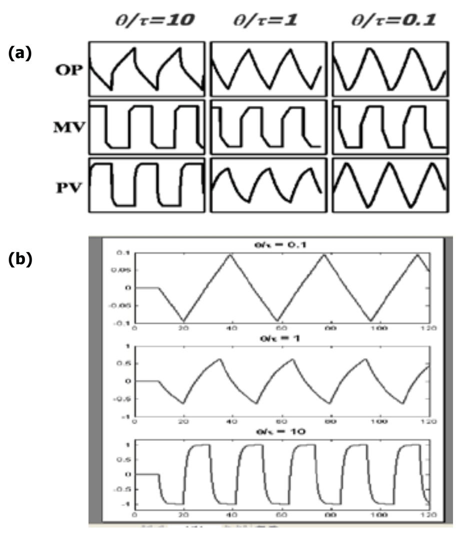

Fig.13: (a) Wave shape in a loop affected by stiction as modified by process dynamics (ratio θ/τ) for a FOPTD process. (b) Different wave shapes generated by a relay feedback controller on a FOPTD process by varying θ/τ

<u>The *Ya*$^+$ technique</u> is an extension of the technique originally proposed by Yamashita (2006), which is based on the analysis of trends MV(OP), that is valve output as function of the control action. Its applicability would seem low, because usually only PV and OP are recorded on industrial DCS; in the case of flow control (FC), the controlled variable can be considered known, being proportional to the valve opening. As FC loops are a large majority of base control loops (about 2/3 in the application presented here), the applicability of this technique is large. It is much larger for newly designed plants (for instance power plants with redundant instrumentation) and it will increase in a next future with the diffusion of field bus communication systems and related available information.

In the presence of stiction, the trend changes from linear to a typical parallelogram shape (Fig.14): the horizontal part indicates that the valve opening does not change for increasing controller output.

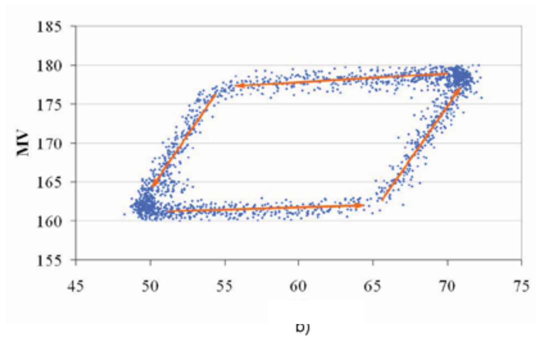

Fig. 14: Valve position (MV) as a function of the controller output (OP) in the presence of stiction (industrial data)

Following Yamashita (2006), the pattern can be approximated by means of three simple symbols: increasing (I), decreasing (D), and steady (S). Possible combinations of symbols for the stiction pattern reported above are represented in Figure 15, as: ID, IS, II; SD, SS, SI; DD, DS, DI.

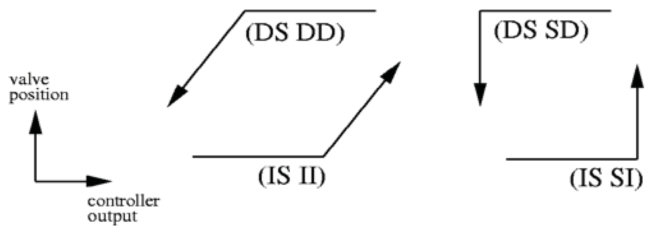

Fig. 15: Qualitative shapes observed in sticky valves.

By combining the symbols for OP and MV signals, a representation of the development in an (OP, MV) plot over time can be obtained. Based on these considerations and counting the duration of time sequences, a stiction index ρ can be defined; values of $\rho > \rho° = 0.25$ (threshold value for a random signal) are indication of possible stiction in the valve. These considerations have been extended to include different stiction patterns observed in industrial data, for instance the one reported in Fig.16.

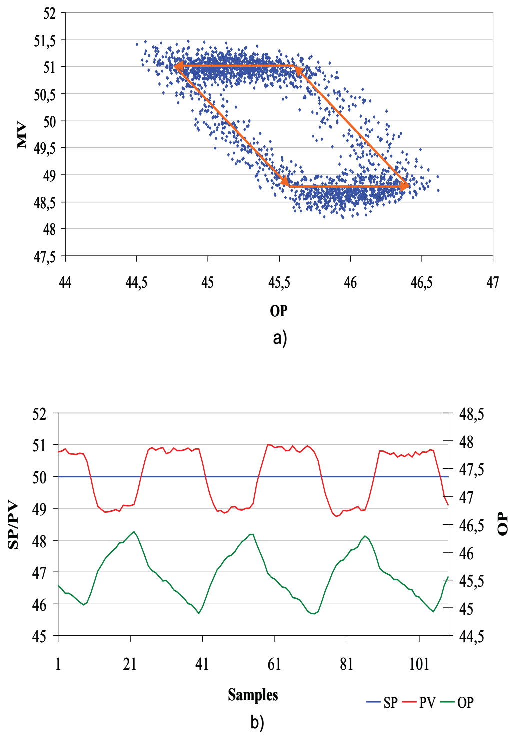

Fig. 16: a) A different MV(OP) pattern observed in industrial data, in the presence of evident stiction (b)

Other patterns are possible depending on valve type (direct/inverse action) and on DCS configuration, as reported in Figure 17.

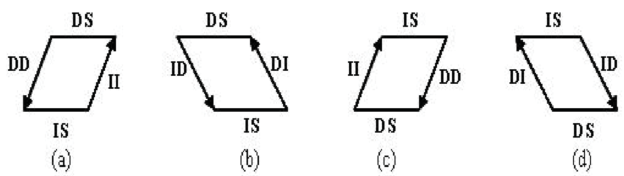

Fig. 17: Additional stiction patterns

They can be explained by the presence of a (even small) delay between OP and MV is present, caused for instance by the combined action of different factors such as: backslash phenomena, valve positioner dynamics, signal quantizer and so on. They can be reproduced by simulation by means of a widely used stiction model, with suitable modifications (Choudury et al, 2005).

Different stiction indices have been defined to be able to identify their presence in industrial data, namely: ρ_B, ρ_C, ρ_D, (in addition to a ρ_A=ρ), accounting for the appropriate coupled sequences of I, S, D primitives (further details in Scali and Ghelardoni, 2008).

For a set of 52 data acquisitions, 11 additional loops were indicated as sticky, according to the new index ρ_B, while would not be indicated by ρ_A, as summarized in table 1 (threshold value is 0.25). During the implementation and field validation of this project, only A and B stiction patterns were encountered, owing to some practical constraints adopted in the DCS configuration; C and D patterns may be found in the most general case.

Table 1: Details for the additional 11 sticky loops

Loop #	ρ_A	ρ_B
xxFC1	0.2459	0.4146
xxFC2	0.1941	0.2648
xxFC3	0.2238	0.3444
xxFC4	0.2303	0.2817
xxFC5	0.1889	0.2961
xxFC6	0.2071	0.4882
xxFC7	0.1352	0.2596
yyFC1	0.1200	0.3621
yyFC2	0.1797	0.3712
yyFC3	0.1614	0.3407

A.2 Identification

The Identification Module receives form the AIM module loops with constant SP labelled as NG (No Good) caused by improper tuning and loops labelled as NC (Not Classified) with variable SP.

<u>In the case of constant SP</u>, the recorded lops dynamics refer to a poor performing response caused by the presence of an external perturbation (Figure 18). A Simplex based search technique has been adopted for the solution of this problem, with some modifications to the original algorithm (Nelder and Mead, 1964), in order to overcome the problem of getting stuck in local minima and of managing the presence of constraints. Further details are reported in Rossi (2007) and Rossi and Scali (2009).

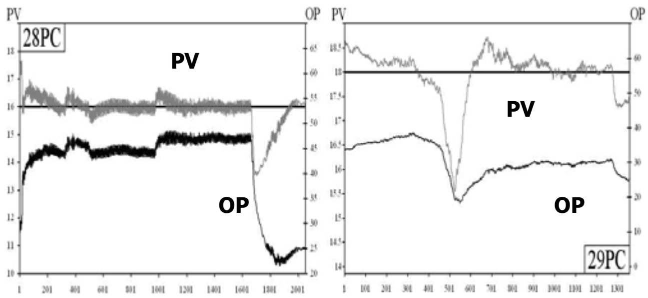

Fig. 18: Poor loop responses caused by external perturbation

Both process and disturbance dynamics are modelled as second order plus time delay systems, with parameters K, K_d (gains); θ, θ_d (delays); τ, τ_d (time constants); ξ, ξ_d (damping factors):

$$P(s) = \frac{K \cdot e^{-\theta s}}{\tau^2 s^2 + 2\xi\tau s + 1}; \quad P_d(s) = \frac{K_d \cdot e^{-\theta_d s}}{\tau_d^{\,2} s^2 + 2\xi_d \tau_d s + 1} \qquad (2)$$

The identification problem can be stated as the minimization over the model parameters vector V, of MSE between recorded and computed values (N is the number of samples):

$$\min_V (MSE); \quad MSE = \sum_{i=1}^{N} (Y_i - Y^{\wedge}{}_i)^2 \qquad (3)$$

In the case of variable SP, an ARX process model is identified (Ljung, 1999); in discrete form:

$$y_k + a_1 y_{k-1} + \cdots + a_n y_{k-n} = b_1 u_{k-L-1} + \cdots + b_m u_{k-L-m} + e_k \quad (3)$$

where: y is the output (PV), u is the input (OP), L is the time delay, n and m are model order. From past values of y and u, it is possible to define the output predictor as:

$$\hat{y}_k = \varphi_k^T \theta, \qquad (4)$$
$$\begin{cases} \varphi_k = \left[-y_{k-1} \quad \cdots \quad -y_{k-n} \quad u_{k-L-1} \quad \cdots \quad u_{k-L-m}\right]^T \\ \theta = \left[a_1 \quad \cdots \quad a_n \quad b_1 \quad \cdots \quad b_m\right]^T \end{cases}$$

Once a time window has been fixed of length equal to N sampling times, (details are given below), a suitable quadratic function of the error between predicted and recorded values:

$$V_N(\theta) = \frac{1}{N}\sum_{k=1}^{N}(y_k - \hat{y}_k)^2 = \frac{1}{N}\sum_{k=1}^{N}({y_k}^2 + \theta^T \varphi_k \varphi_k^T \theta - 2\theta^T \varphi_k y_k) \quad (5)$$

and, by minimizing V_N with respect to model parameters:

$$\theta^* = \left[\sum_{k=1}^{N}\varphi_k \varphi_k^T\right]^{-1}\left(\sum_{k=1}^{N}\varphi_k y_k\right) \quad (6)$$

The value of the delay L should be known; this limitation can be overcome by repeating the computation of θ^* for different values of L (from 0 to L_{max}) and choosing the delay θ^* corresponding to minimum values of V_N. The initialization of the predictor requires the knowledge of data for $N_0 = max(n,m+ L_{max})$ sampling times, before $k=1$.

Several criteria can be defined to evaluate the accuracy of identification. Here, a closed loop index has been adopted, as the scope of identification is modelling for control purpose. Given the SP sequence in the examined window, values of the output variable vector $y'_1, ..y'_N$, for the actual controller and the identified model are computed, originating the index:

$$EV_{CL} = 1 - \frac{\sum_{k=1}^{N}(y_k - y'_k)^2}{\sum_{k=1}^{N}(y_k - y_{mean})^2} \quad (7)$$

where: y_{mean} represents average value for the output. EV_{CL} represents an explained variance, with values less than 1 (and generally not less than 0).

The application of the procedure is different according to the number of SP changes, for instance primary loops or loops under cascade / advanced control.

In the case of only one SP change, only one time window is selected and the procedure is applied as described above. The starting point is fixed n_0 sampling times before the time of SP change, while the final point is taken when the response has settled within a 5% of the output value. The identification is considered successful if $EV_{CL} \geq 0.80$.

For cases of variable SP, time windows of about 20 minutes for FC loops (about one hour for other type of loops) are chosen and the identification procedure is applied on each window. The step response of the two models having larger value of EV_{CL} are compared, as:

$$MD = 1 - \frac{\frac{1}{M}\sum_{k=1}^{M}(y_k^{SR1} - y_k^{SR2})^2}{\sum_{k=1}^{M}\left(\frac{y_k^{SR1} + y_k^{SR2}}{2}\right)^2} \quad (8)$$

where: y_k^{SR1}, y_k^{SR2} are *k-th* step response coefficient of model 1 and 2. The identification is considered successful for $MD \geq 0.95$ (and $EV_{CL} \geq 0.80$). Threshold values have been assumed after intensive simulations and applications on loop data. Referring to Figure 19 and Table 2, acquired data are divided in 8 time windows, identification is heavily wrong for windows 2 and 4 ($EV_{CL} < 0$), is not considered reliable enough for windows 1,3,5,6 ($EV_{CL} < 0.80$), is considered successful for windows 7 and 8 ($EV_{CL} \geq 0.80$); for these two windows $MD = \geq 0.986$ and then the identified model is accepted.

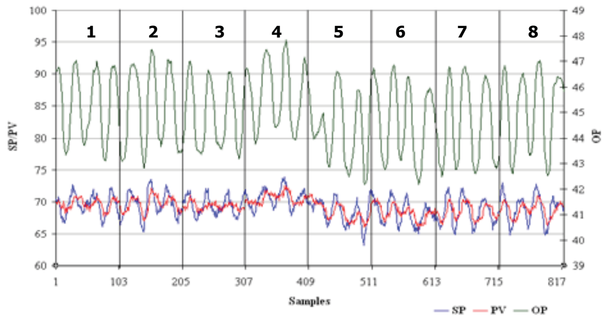

Fig. 19: Variable SP loop and time windows divisions

Table 2: Values of EV_{CL} in the 8 time windows

t.w.	1	2	3	4	5	6	7	8
EV_{CL}	*0.51*	*-40*	*0.66*	*-29*	*0.58*	*0.74*	*0.89*	*0.80*

Identification may be not successful for several reasons, for instance: non linearity of real process or not optimal choice of ARX model order (n, m). Nevertheless, main causes of failure are to be found in the presence of valve stiction or external disturbances.

In the first case, a failure is "desirable" (a linear model being not reliable in this case) to avoid the adoption of an incorrect model and a wrong suggestion about cause (retuning instead of stiction).

In the second, it may be possible to find few time windows not heavily affected by disturbances: this is the logical behind the choice of comparing models identified in two different time windows and requiring large values of MD and EV_{CL}; more details in Mervi (2007).

A.3 Upgrading Indices

Once the identification has been successfully carried out and a process model is available, the optimal tuning is evaluated according to different available techniques, selected at the configuration stage.

The performance improvement predicted on the basis of the identified model, is evaluated by means of an upgrading index Φ:

$$\Phi = \frac{IAE_{Act} - IAE_{Best}}{IAE_{Act} - IAE_{Min}} \quad (9)$$

where: IAE is the Integral of Absolute Error of the response for the actual regulator (*Act*), for the best controller having PI/PID structure (*Best*) and for the optimal one for the identified model (*Min*). For $\Phi \to 0$, the proposed controller is closet to the optimal one; for any $\Phi > 0$ there are improvements, but a threshold has been assumed to implement the new retuning (the proposed threshold $\Phi° = 0.50$, has been decreased to *0.40*, after field validation).

Other indices allow to evaluate the real performance improvements on the plant, before and after retuning, in the two cases of primary loops (with rare SP changes, mainly step-wise) and secondary loops (with frequent SP changes, imposed by the primary loop acting on them).

For primary loops a new index Φ' is defined, having the same expression (9), with controllers tagged as *Act* and *Best* substituted by *Old* and *New* (to indicate before and after retuning) (Figure 20a).

For secondary loops, the IQI (Improvement Quantification Index) is defined, to evaluate the error between recorded SP and PV values before and after retuning (Figure 20b):

$$IQI = 1 - \frac{\frac{1}{N}\sum_{i=1}^{N}\left(SP_i - PV_i\right)^2}{\frac{1}{N}\sum_{i=1}^{N}\left(SP_i - SP_{medio}\right)^2} \quad (10)$$

where: N: is the number of sampling times where the tuning is maintained as constant, SP_i: , PV_i , i-th value of SP and PV, and, SP_{ave}, is the average SP value in the time range where tuning parameters are left constant.

Values of IQI close to 1 indicate perfect control, while small or negative values indicate scarce performance.

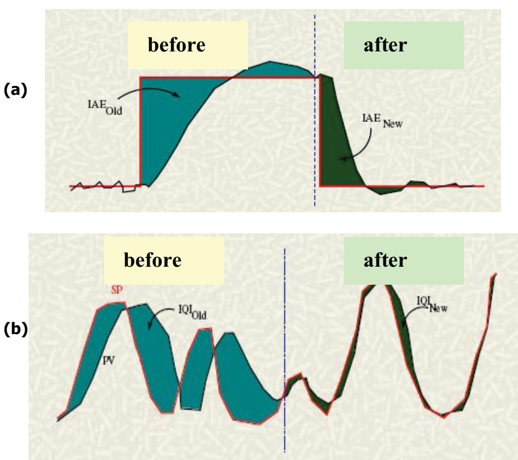

Fig. 19: Representation of the upgrading indices for: constant (a) and variable SP loops (b)

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