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A System for Advanced Performance Monitoring: Application to Complex Plants of the Chemical Industry

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This paper illustrates the results of the off-line application of an advanced performance monitoring system to complex plants of the chemical industry. The system analyses data recorded by the DCS during routine operations and issues automatic verdicts about the performance of the basic control loops. Indications of causes of low performance (controller tuning, valves, disturbances) and different strategies to adopt (retuning, valve maintenance, upstream actions) are also given. The overall system architecture is firstly illustrated, with characteristics of the modules which accomplish different tasks of performance analysis, verdicts emission and operator support. A synthesis of the main techniques and algorithms adopted in the system is also given, together with differences among different versions of the system, according to available information on the plant. Examples of field results are then presented, with illustration of loops performance assessment and actions suggested by the monitoring system.

1. Introduction

Control loop performance assessment (CLPA) 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 sources of malfunction are external perturbations, poor controller tuning and valve problems.

In Figure 1 (left), the 3 main variables of a control loop are indicated: Set Point (SP), Controlled Variable (PV) and Controller Output (OP). The valve position (MV) is not available in general and malfunctions have to be diagnosed by referring only to these three signals transmitted in 4-20 mA current. This constitutes the so-called “standard” diagnostics. In new design plants, the adoption of intelligent instrumentation, valve positioners and field bus communication systems increases the number of variables which can be acquired and analyzed by a monitoring system (Figure 2, right). The positioner acts as an inner control loop on the valve position and allows to speed up the valve response. In addition to SP, OP and PV, DS, P, MV represent the variables typically made available by the positioner (for a maximum of 6 variables). The Drive Signal (DS), is the electric signal generated by the internal controller (C_i) which, through the I/P converter, generates the pressure signal (P) acting on valve membrane, thus determining the position of the stem. The knowledge of MV allows a more precise diagnosis of loop and valve problems, especially stiction (static-friction), which is known to be the most common cause of performance degradation (Jelali and Huang, 2010). Cause of malfunctioning in valves 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, I/P malfunction; details are reported in Bacci di Capaci et al. (2013).

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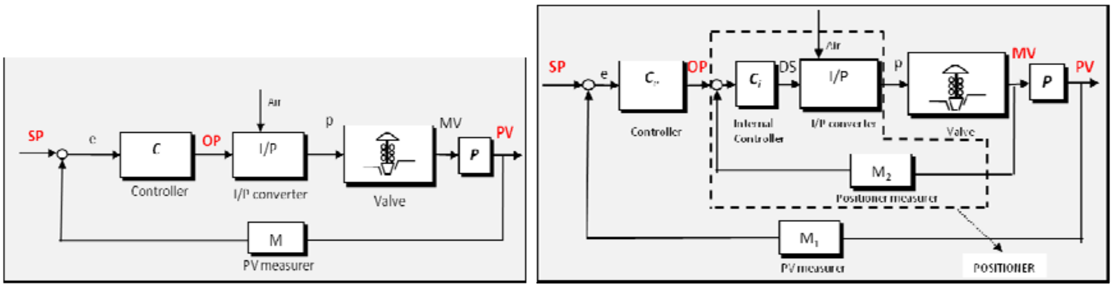

Figure 1: The reference scheme for a control loop with: left) standard equipment; right) advanced devices

The research group of the Chemical Process Control Laboratory (CPCLab) of the University of Pisa is active in control loop monitoring systems since many years. The PCU (Plant Check Up) is the name of the performance monitoring system now installed on several industrial plants. Different versions of the system are available, depending on the equipment and the measurements available in the plants; periodically new versions of the system are released. The basic version of PCU is now supervising more than 1200 loops of refinery plants. The system analyses data recorded by the DCS during routine operations and indicates causes of low performance and strategies to adopt using the three “standard” variables. More recently, an advanced version of the diagnostic system has been developed. This version of PCU uses 4 variables (SP, PV, OP and also MV) and grant a more precise - “advanced” - diagnostics. This system has been firstly tested on a pilot plant and later implemented in an industrial power plant (Bacci di Capaci et al., 2013).

The present paper has the following structure: section 2 describes the two main versions of the performance monitoring system (PCU), giving some details on the whole architecture and the specific modules with the main techniques and algorithms implemented; in section 3 a comparison between the standard and the advanced version of the system is presented; section 4 and 5 illustrate problems and results of the off-line application of the system to chemical industrial plants; conclusions and next steps are reported in section 6.

2. The system architecture

A schematic representation of the last version of the “standard” PCU is reported in Figure 2 (left). A full description of the version implemented online in a refinery plant is reported in Scali and Farnesi (2010); a synthesis of the latest version is reported below.

The Initialization Module (IM) imports parameter values 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 is stopped. In these cases, the loop receives a (definitive) label of NA: Not Analyzed.

The Anomaly Identification Module (AIM) 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 labeled as NC (Not Classified) and sent to the Identification and Retuning 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’s approach (Hägglund, 1995; 1999), with suitable modifications of internal parameters, based on field calibration (Scali et al., 2010). According to Hägglund’s criterion (1995) an oscillation is considered relevant if its Integral of Absolute Error overcomes an assumed value ($IAE > IAE_{\mathrm{lim}}$), for a certain number of times (N_{lim}), in the supervision time window T_{sup}. IAE and IAE_{lim} are defined as:

$$IAE = \int_{t_i}^{t_{i+1}} |e(t)|\, dt; \qquad IAE_{lim} = \frac{2a\cdot RangePV}{\omega_u} \tag{1}$$

where e is the error (e = PV - SP), t_i and t_{i+1} are two zero crossing times. IAE_{lim} depends on the range of the controlled variable PV, the amplitude, a and the loop critical frequency $\omega_u = 2\pi/P_u$ (if not known, it can be estimated from the value of the integral time constant (τ_i) of the controller, in the hypothesis of a Ziegler & Nichols tuning: $\tau_i = P_u/1.2$). The technique allows one to detect oscillations in the frequency range of interest (low-middle) and to disregard high frequency oscillations, associated with instrumentation noise.

In the case of both Hägglund’s 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 I&R Module. 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.

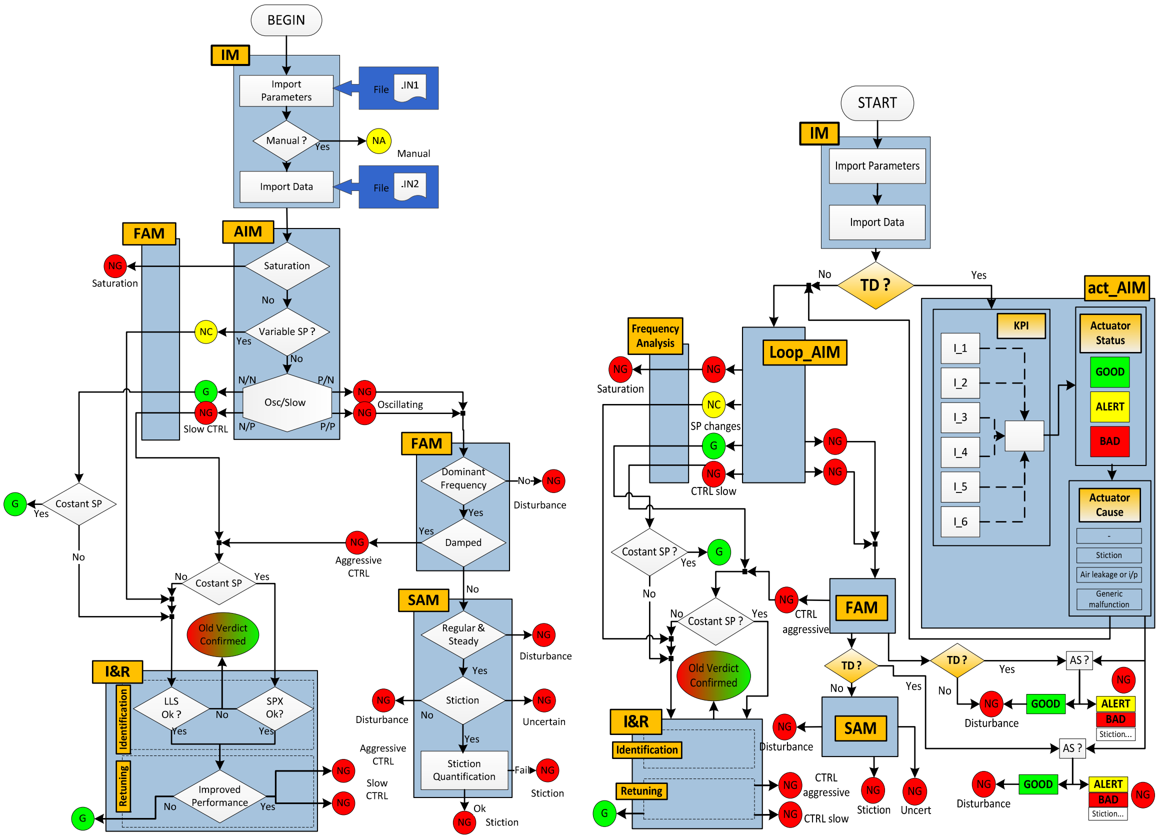

Figure 2: Schematic representations of different PCU versions: left) standard PCU; right) advanced PCU

The Frequency Analysis Module (FAM) has the scope of separating irregular oscillations from regular ones on the basis of a power spectrum which computes dominant frequencies; irregular loops are labeled 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 Identification & Retuning Module (I&R) accomplishes process identification and, if successful, controller retuning and evaluation of performance improvements. It receives from the AIM module loops with constant SP labeled as NG (Not Good) caused by improper tuning and loops labeled as NC (Not Classified) with variable SP. Identification in the case of constant SP is performed using a Simplex based search technique. In the case of variable SP, being typical of secondary loops under cascade control, an ARX process model is identified. When model identification is successful, new tuning parameters are then calculated. 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. The nominal performance improvement, predicted on the basis of the identified model, is evaluated by means of the upgrading index *Φ*:

$$\phi = \frac{IAE_{Act} - IAE_{Best}}{IAE_{Act} - IAE_{Min}} \tag{2}$$

where *IAE* is the Integral of Absolute Error of the step response for the actual regulator (*Act*), for the best controller having PI/PID structure (*Best*) and for the optimal regulator (*Min*). For *Φ* → 1, the proposed (*Best*) controller is closed to the optimal one; for any *Φ* > 0 there are improvements, but a threshold has been assumed to implement the new tuning: *Φ* = 0.40, fixed after field validation (Scali and Farnesi, 2010).

The Stiction Analysis Module (SAM) analyses data of NG oscillating loops and performs different tests to detect the presence of valve stiction and to quantify its amount. This module has been recently improved by Bacci di Capaci and Scali (2014a). About stiction detection, four techniques are applied: the Relay based fitting of values of PV (Rossi and Scali, 2005), the improved qualitative shape analysis (Scali and Ghelardoni, 2008), the Cross-Correlation (Horch, 1999) and the Bicoherence (Choudhury et al., 2005). Stiction quantification is performed only on loops clearly indicated as affected. A grid search algorithm with a

Hammerstein system identification (a nonlinear stiction model plus a linear ARX model) allows one to estimate the unknown MV signal (Bacci di Capaci and Scali, 2013). To increase the reliability of stiction estimations, data can be divided in sets and the method can be applied separately (Bacci di Capaci and Scali, 2014b). The possibility of diagnosing, quantifying and compensating stiction is nowadays included in some CLPA systems, proposed by software houses or published in the specific literature (Brásio et al., 2014).

A schematic representation of the "advanced" PCU is reported in Figure 2 (right). A new analysis path oriented to actuator diagnostics (module Act_AIM) is activated by the availability of MV and TD (Travel Deviation), defined as the difference between real and desired valve position TD = MV-OP. Six specific KPI indices and a specific logic of assigning performance grades are implemented. Module Act_AIM issues verdicts of state and causes of anomalies of the actuator: Stiction, Air leakage or I/P malfunction and Generic Malfunction can be diagnosed. These verdicts are definitive and affect the other analyses: the loop path is activated subsequently to actuator path and some more accurate tests in FAM and SAM are performed.

3. Comparison of PCU versions

The knowledge of MV and TD permits a successful diagnosis of malfunctions that are not detectable simply by using OP and PV; that is the actuator analysis implemented in advanced PCU recognize malfunctions which otherwise would be hidden by loop dynamics. In Bacci di Capaci et al. (2013) a detailed comparison of the results between the two releases of PCU system, based on 3 and 4 variables, applied to the same data, is presented. Here, in Table 1, only some results are briefly reported. For example, advanced PCU is able to diagnose malfunctions in the actuator (not yet visible in the loop) and issues correct verdicts (Stiction, Leakage, I/P Malfunction), while standard PCU wrongly emits a verdict of good performance.

Table 1: Comparison of results on pilot plant data: Standard PCU vs Advanced PCU

Case		Good	Disturbance	Stiction	Leakage	I/P malfunction
Standard PCU	Loop Status	Good	Disturbance	Good	Good	Good
Advanced PCU	Loop Status	Good	Disturbance	Good	Good	Good
	Actuator Status	Good	Good	Stiction	Leakage	I/P malfunction

4. Application on industrial data

The PCU system has been recently applied off-line to data obtained from control loops of two petrochemical plants of ENI-Versalis: ethylene plant of Porto Marghera and butadiene plant of Ravenna (Italy). The results of this application are illustrated in this section.

Ethylene is produced by steam cracking from virgin naphtha. The mixture of gas and liquid olefins, obtained in two gas burners, is separated at low temperature and high pressure through a series of columns and reactors: demethanizer, deethanizer, catalytic hydrogenation reactor, ethylene - ethane splitter and then depropanizer, propylene - propane splitter and debutanizer. Whereas, butadiene is obtained from crude butane. The plant is composed of a extractive distillation with a specific solvent of a raffinate product, a degassing for the recovery of the solvent and a two-stage distillation to get high purity 1,3-butadiene and other coproducts.

Control loop regulation is performed by pneumatic valves with standard equipment, therefore only SP, PV and OP data are available. No valve positioners are used, so the standard version of PCU has been applied (Figure 2, left). 83 loops of the ethylene plant and 15 loops of the butadiene plant have been assessed respectively. Repeated acquisitions for the same 98 loops have been collected, for a total of 1180 data sets.

On the basis of the more frequent verdict, the system has allowed one to assess:

- 16 control loops operating in manual;
- 36 loops with good performance (G);
- 26 loops Not Good (NG) with controller tuning problems (5 too aggressive and 21 too sluggish);
- 15 loops NG with valve stiction;
- 3 loops NG affected by external disturbances;
- 2 loops with low performance (NG) but unclear source of malfunction.

A good matching between the verdicts issued by the PCU system and the indications of control operators has been achieved. The system has assessed overall 46 loops with low performance. Only 15 valves are indicated with problems and this will give an economic saving since unnecessary maintenance of the other valves - which does not improve performance - can be avoided. 26 loops are reported with controller problems; in 8 cases the retuning is suggested. This allows operators to save time during campaign of retuning since they have precise suggestions for critical loops. Therefore, useful indications have been obtained with the standard PCU; a more precise assessment would be possible with the advanced version of the system.

5. Example of results

Three illustrative examples are shown in the sequel as representative of a category of loops.

1) Loop FC1 (from butadiene plant, with PI control and constant SP) represent a case of initial mismatch between PCU and operator verdicts, for which a recalibration of Hägglund's criterion on oscillating loops is needed. Default values for the parameters are: $2a = 0.02$, $N_{lim} = 10$, $T_{sup} = 50P_u$. With a value of $2a = 0.02$, the verdicts from AIM and SAM modules are always NG, indicating disturbance as cause of malfunction in 11 out of 12 acquisitions. On a practical level, indeed, these oscillations - due to their small amplitude (compare Figure 3, top) - are considered *acceptable* and the PCU verdicts seem too severe, as a sort of False Alarms (Figure 3, bottom left). The results obtained with an increased value of Hägglund's parameter ($2a = 0.06$) are completely different (12 cases of G) and perfectly aligned to operator indications (Figure 3, bottom right).

2) Loop FC2 (from ethylene plant, with PI control and variable SP) is a clear case of incorrect tuning. The verdicts from AIM and I&R modules are NG, for 10 out of 12 acquisitions, indicating as cause: sluggish controller (Figure 4, left). The identification is always successful and the old settings ($K_c = 0.4$, $\tau_i = 150$), should be changed to new ones: $K_c = 2.2\text{-}2.9$, $\tau_i = 30\text{-}45$. An increase of integral action is then suggested; the upgrade index based on the model (see Section 2) is always very high: $\Phi = 0.78\text{-}0.99$ (Figure 4, right). Future acquisitions will permit to check the predicted improvements obtained with the suggested retuning.

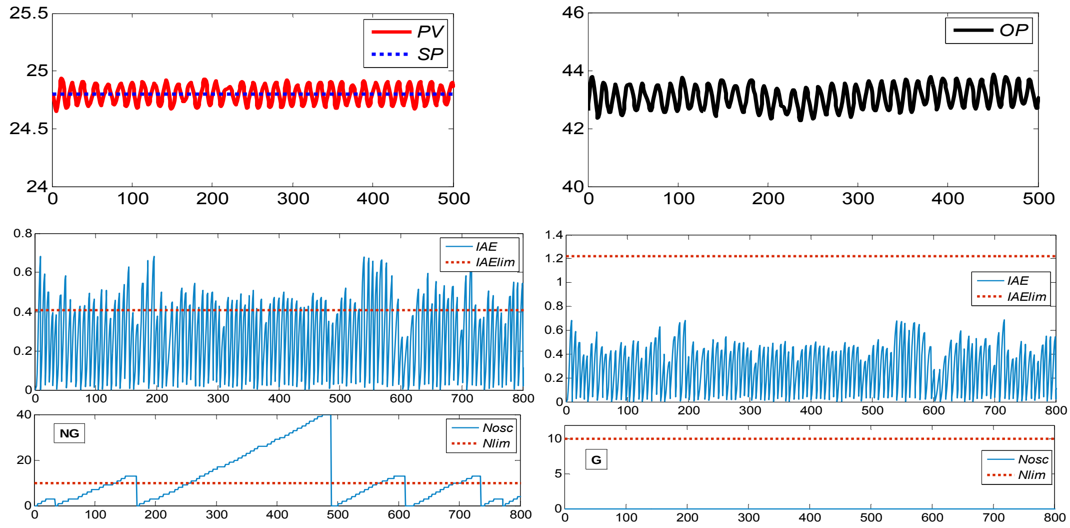

Figure 3: Loop FC1. Top) time trends; bottom) Hägglund's test: left) NG with 2a=0.02; right) G with 2a=0.06

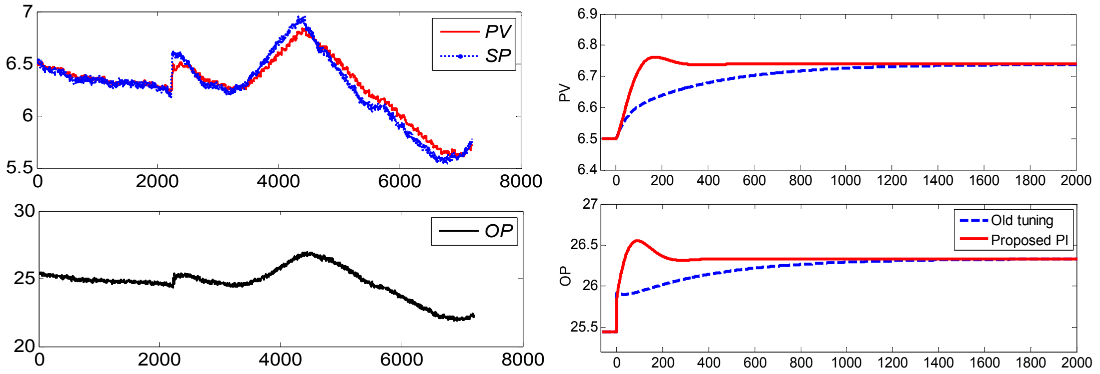

Figure 4: Loop FC2. Left) time trends; right) step responses for computation of retuning index Φ

3) Loop FC3 (from ethylene plant, with PI control and variable SP) is a typical case of valve malfunction. This loop has been indicated as affected by stiction in 11 out 12 acquisitions. The presence of stiction is clearly recognizable by the PV and OP shapes (close to square waves and triangles, respectively in Figure 5, left). Moreover, the plot of PV(OP) shows evident stiction characteristics (Figure 5, right) since in FC loops PV is proportional to MV. About stiction quantification, the *S* parameter is rather constant for the 11 NG acquisitions

(see Table 2). Note that 1 % of stiction is enough to cause performance problems (Jelali and Huang, 2010). A good valve maintenance will surely bring to an improvement of performance with an elimination of stiction.

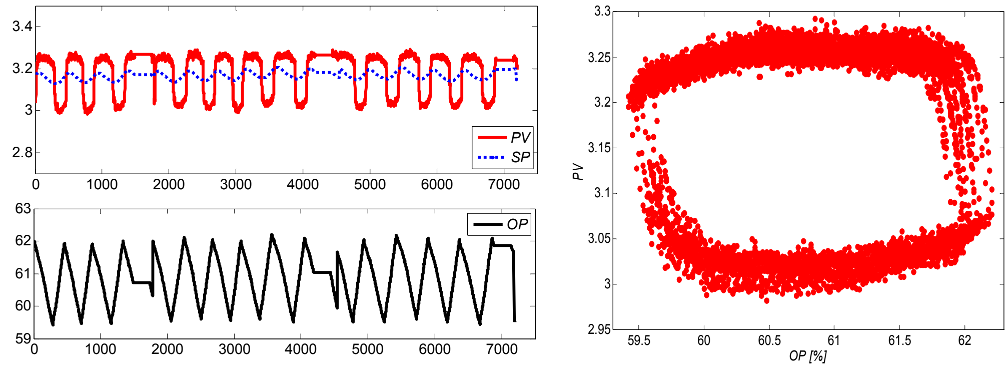

Figure 5: Loop FC3. Left) time trends; right) PV(OP) diagram with the typical shape of a sticky valve

Table 2: Loop FC3. Results of stiction quantification, parameter S for different acquisitions

Acquisition	1	2	3	4	5	6	7	8	9	10	11	mean	std deviation
Stiction *S* [%]	2.4	2.0	1.8	2.5	2.2	2.4	2.2	2.3	2.0	2.5	1.8	2.2	0.26

6. Conclusions

A well-established performance monitoring system (PCU) has been described with details about its different versions. The application of the standard version of the system to data obtained from control loops of complex chemical plants have been presented. A good matching between the verdicts issued and the indications of the operators has been achieved. Significant benefits can be obtained: saving costs of unnecessary maintenance (good valves) and saving time following suggestions about retuning of low performing controllers. More precise indications would be possible with the advanced PCU (further distinction of causes and corrections).

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